

# Quasi-Elastic Scattering of Neutrinos and Antineutrinos at MINERvA

Joint Experimental-Theoretical Physics Seminar  
10 May 2013, Fermilab

David Schmitz, University of Chicago

# Some Opening Remarks

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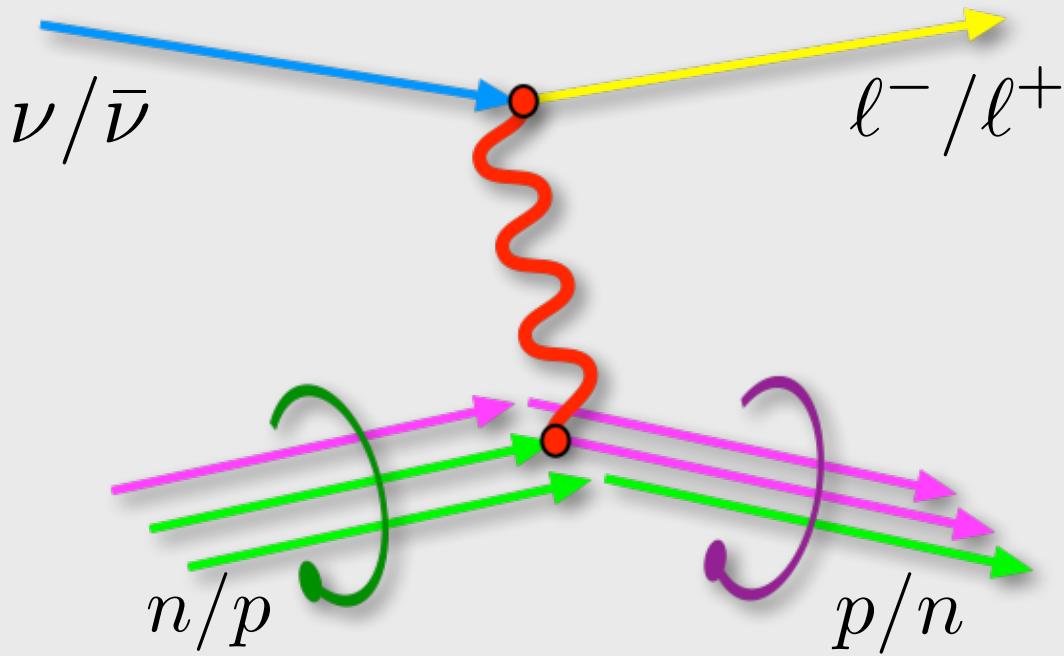
- The physics of neutrino-nucleus scattering is an important component of the on-going global effort to reveal the complete nature of neutrinos
- Scattering from heavy nuclear targets in neutrino experiments introduces a level of complication whose impact needs to be understood
- Modern experiments are providing large, detailed data sets to better understand these processes
- Close ties to nuclear physics. Both in terms of expertise and valuable complementary measurements (electron-nucleus scattering)
- These measurements are needed to improve  $\nu$ -N modeling for use in future neutrino experiments

# Outline

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1. Charged-current quasi-elastic (CCQE) scattering
  - Historical treatment vs. recent considerations
2. MINERvA's measurement of QE scattering for  $\nu$  and  $\bar{\nu}$ 
  - The experiment
  - Isolating a QE sample
  - Systematic uncertainties
  - Interpretation of the results ( $d\sigma/dQ^2$  and hadron energy)
3. Future outlook
4. Closing remarks

# What Is Quasi-Elastic Scattering?



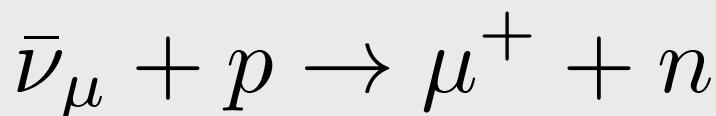
## CCQE scattering

Neutrino or antineutrino  
scattering from a  
free or bound nucleon

No pions in the final state

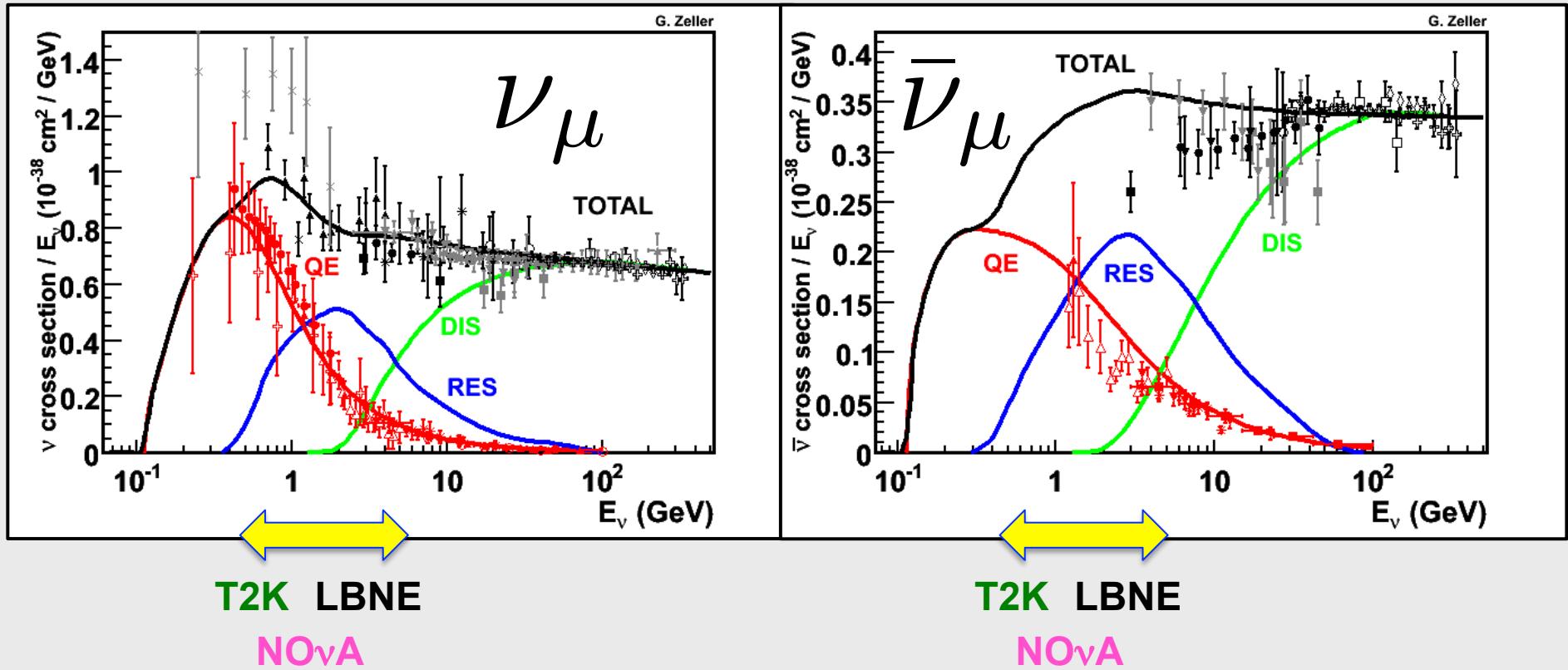


Neutrino transformed  
to a charged lepton



# What Is Quasi-Elastic Scattering?

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



Accelerator neutrino experiments in the energy region  
most complicated by nuclear environment.

# Neutrino-Nucleon QE Scattering

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## NEUTRINO REACTIONS AT ACCELERATOR ENERGIES \*

C.H. LLEWELLYN SMITH

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA*

Received 30 August 1971

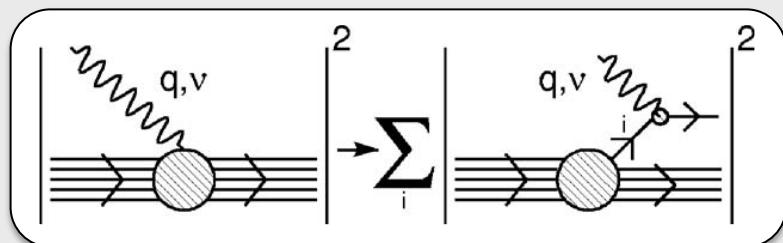
Possible investigations of the properties of weak interactions using high energy neutrinos are reviewed. The use of neutrinos to probe hadron structure is discussed.

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

**Formalism describing QE scattering from FREE nucleons  
included in review article by Llewellyn Smith in 1971**

# Relativistic Fermi Gas For Nucleus

- Working on nuclear models for neutrino scattering can take you far!
- In the *Impulse Approximation*, scatter off independent single nucleons incoherently summed over all nucleons in the nucleus



- If we further assume the *nucleon at rest*, we can determine  $E_\nu$  from the lepton kinematics alone

$$E_\nu^{QE} = \frac{2(M_n - E_B) E_\ell - [(M_n - E_B)^2 + m_\ell^2 - M_p^2]}{2[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

Pretty handy!



## NEUTRINO REACTIONS ON NUCLEAR TARGETS <sup>‡</sup>

R. A. SMITH <sup>#</sup> and E. J. MONIZ <sup>##</sup>  
Institute of Theoretical Physics, Department of Physics,  
Stanford University, Stanford, California 94305

with energies lowered from free particle energies by an average nuclear potential. Although this choice of wave functions corresponds to a nucleus without detailed structure, the dominant features of the nuclear cross section are consistently represented.

Smith, R. A., and E. J. Moniz, 1972, Nucl. Phys. B43, 605.

$M_n$  = neutron mass  
 $M_p$  = proton mass  
 $E_B$  = separation energy  
 $m_\ell$  = lepton mass  
 $E_\ell, \theta_\ell$  = lepton energy and angle

# Historical Approach To QE Scattering

- Basic strategy was the following:

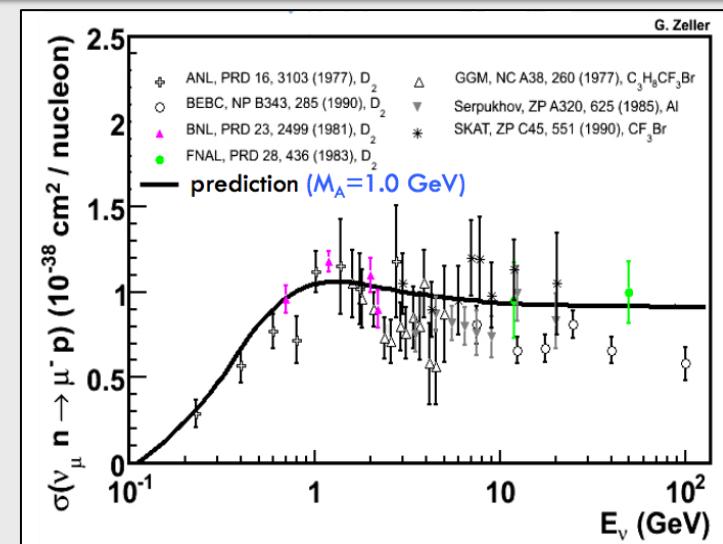
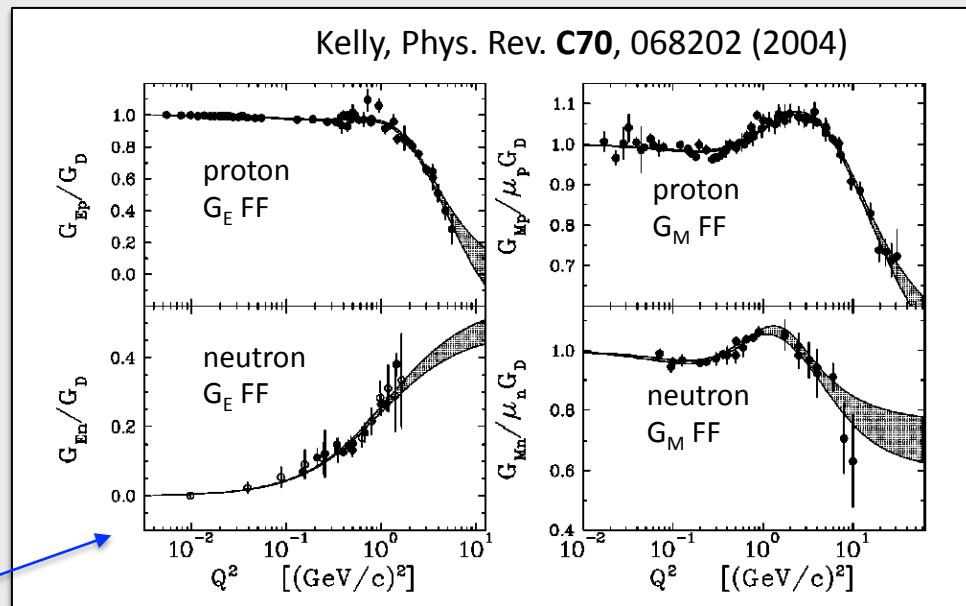
- Start with Llewellyn Smith formalism and assume Relativistic Fermi Gas (RFG) for nucleus

- Form factors in the model parameterize weak charge distributions in the nucleon

- Vector Form Factors measured in electron scattering

- Assume a dipole form for the Axial-Vector Form Factor and use neutrino CCQE scattering data to determine the axial mass parameter

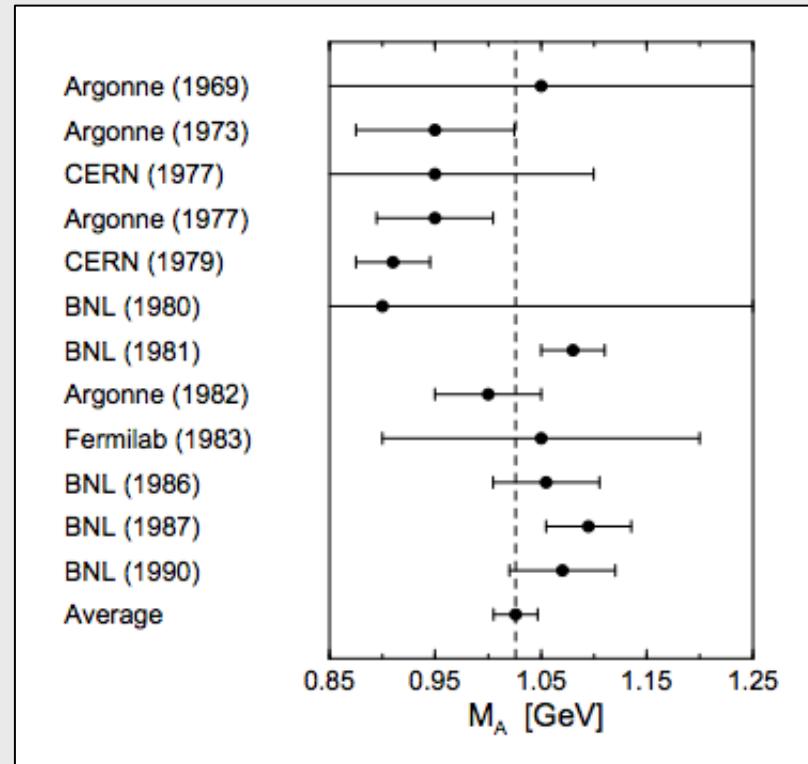
$$F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$



# Historical Approach To QE Scattering

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- Start with Llewellyn Smith formalism and assume Relativistic Fermi Gas (RFG) for nucleus
- Form factors in the model parameterize weak charge distributions in the nucleon
  - Vector Form Factors measured in electron scattering
  - Assume a dipole form for the Axial-Vector Form Factor and use neutrino CCQE scattering data to determine the axial mass parameter



Bernard *et al.*, J. Phys. **G28**, R1 (2002)

$$F_A(Q^2) = F_A(0) \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

Voilà,  
model complete!

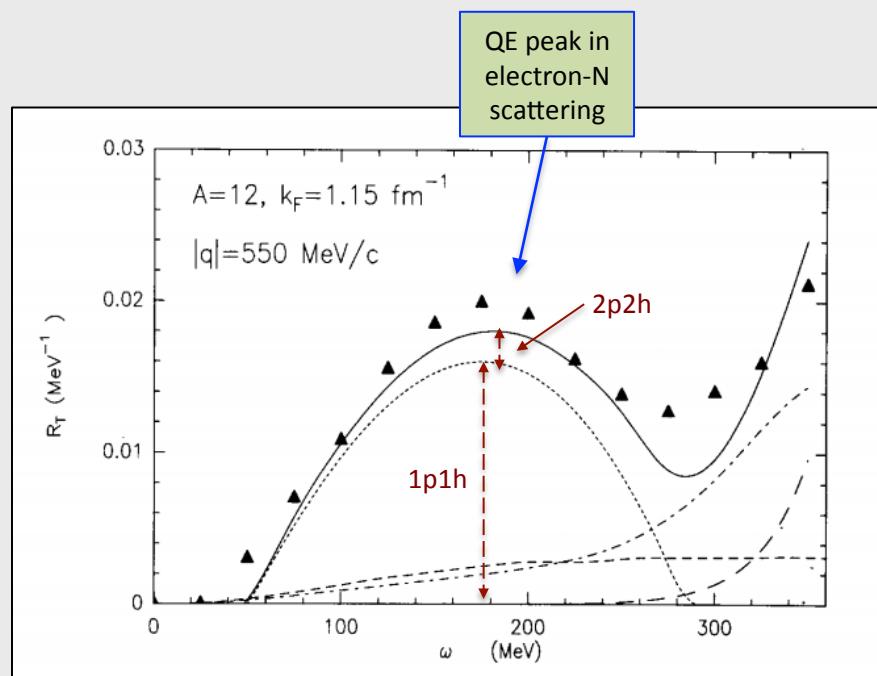
# But Is It Good Enough?

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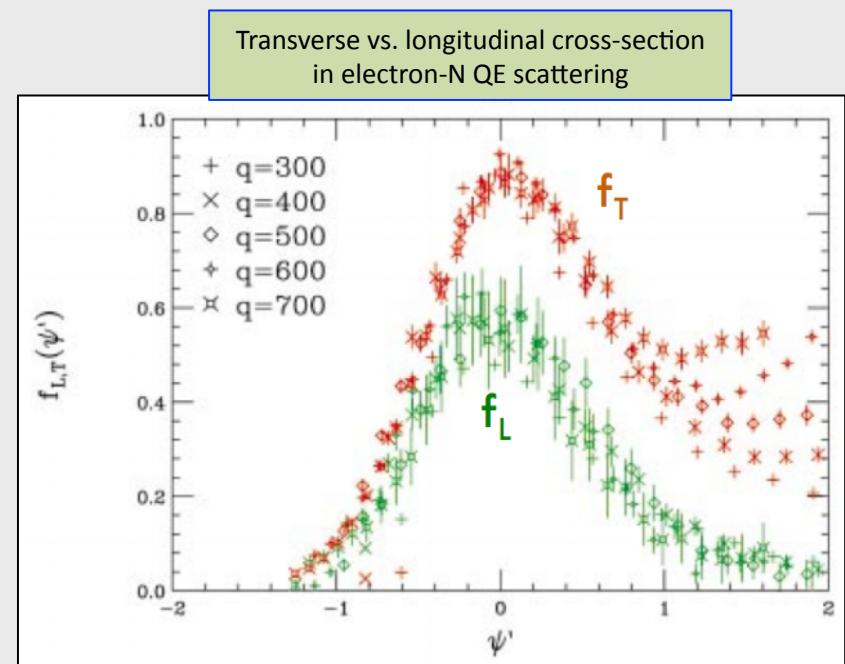
- Both theory and experimental hints tell us that it is not!
- Nucleon-nucleon interactions and 2-body currents are ignored
  - For  $A \geq 12$  *short range correlations (SRC)* affect  $\sim 20\%$  of nucleons
    - These can lead to a nucleon momentum well above the Fermi sea cutoff
    - Correlated nucleon(s) may be ejected when its partner is scattered by an electron or neutrino
    - This change on the hadronic side of the interaction impacts the kinematics and spoils your neutrino energy estimation
  - Other correlations are predicted as well, such as *meson exchange currents (MEC)* which may enhance part of the cross section significantly
    - Again, multi-nucleon emission and impacted neutrino energy reconstruction are consequences

# But Is It Good Enough?

- Experimental evidence seen in *electron scattering* data for a while



Dekker et al. PLB 266, 249 (1991)



J. Carlson, et al., PRC 65, 024002 (2002)

- But has been mostly ignored in *neutrino scattering* until recent experimental evidence (K2K, MiniBooNE) has forced a second look
  - Do these effects apply there? Can we model them? What are their consequences?

# But Is It Good Enough?

- Much work developing models for these effects in neutrino scattering

- Martini et al. PRC 80, 065001 (2009)
- Martini, Ericson, Chanfray, Marteau, PR C81, 045502 (2010)
- Amaro, Maieron, Barbaro, Caballero, Donnelly, PR C82, 046601 (2010)
- Benhar, arXiv:1012.2032
- Alvarez-Ruso, arXiv:1012.3871
- Amaro, Barbaro, Caballero, Donnelly, arXiv:1012.4265
- Nieves, Ruiz Simo, Vicente Vacas, PR C83, 045501 (2011)
- Fernandez-Martinez, Meloni, PL B697, 477 (2011)
- Amaro, Barbaro, Caballero, Donnelly, Williamson, PL B696, 151 (2011)
- Ankowski, Benhar, arXiv:1102.3532
- Meucci, Caballero, Giusti, Udias, arXiv:1103.0636
- Benhar, Veneziano, arXiv:1103.0987
- Amaro, Barbaro, Caballero, Donnelly, Udias, arXiv:1104.5446
- Antonov, Ivanov, Caballero, Barbaro, Udias, Guerra, Donnelly, arXiv:1104.0125

A partial list of recent models

Models are *qualitatively similar*, though not *quantitatively identical*

Are effects identical for *electrons vs. neutrinos*?

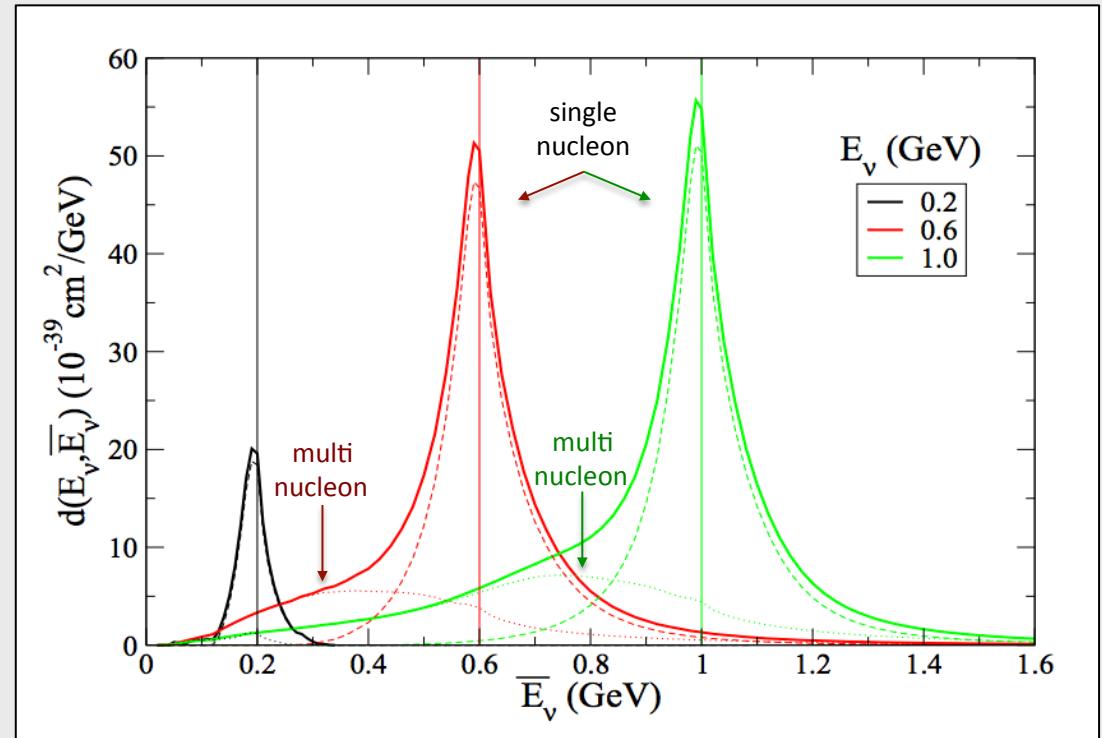
*Different for  $\nu$  and  $\bar{\nu}$ ?*

Understand implications for *neutrino energy* reconstruction

# But Is It Good Enough?

- Recall, formula to the right assumes independent nucleon
- Use of the formula when striking a *correlated nucleon* can be quite wrong
- Even calorimetric reconstruction is challenged since the MC does not simulate the hadronic side of the interaction properly in these events
- Recall, up to 20-30% of the events off correlated pairs

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\ell - [(M_n - E_B)^2 + m_\ell^2 - M_p^2]}{2[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

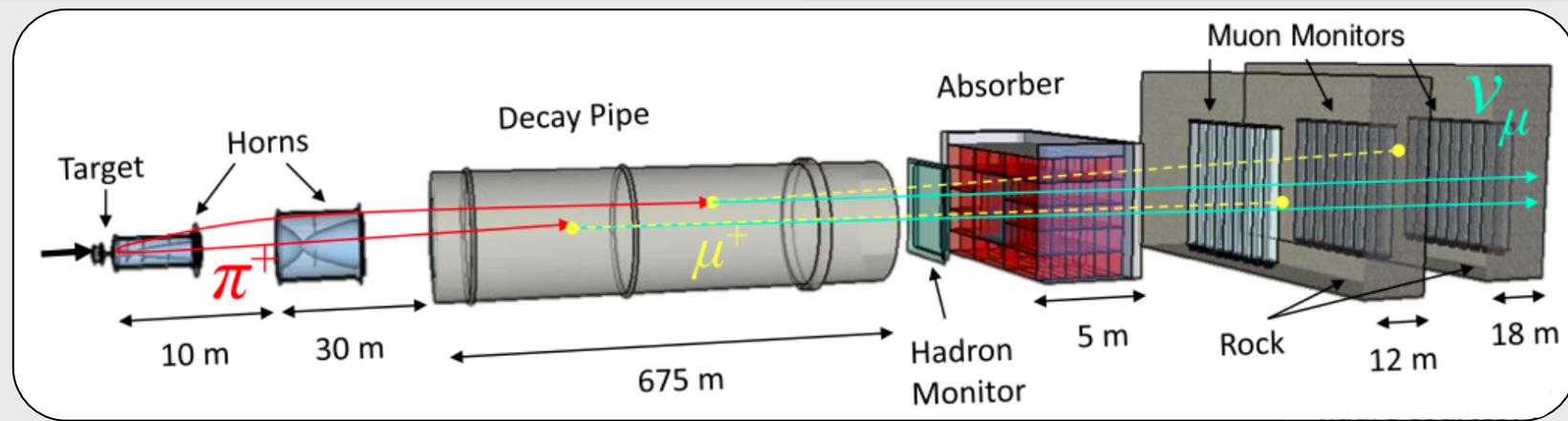


Martini et al. arXiv:1211.1523

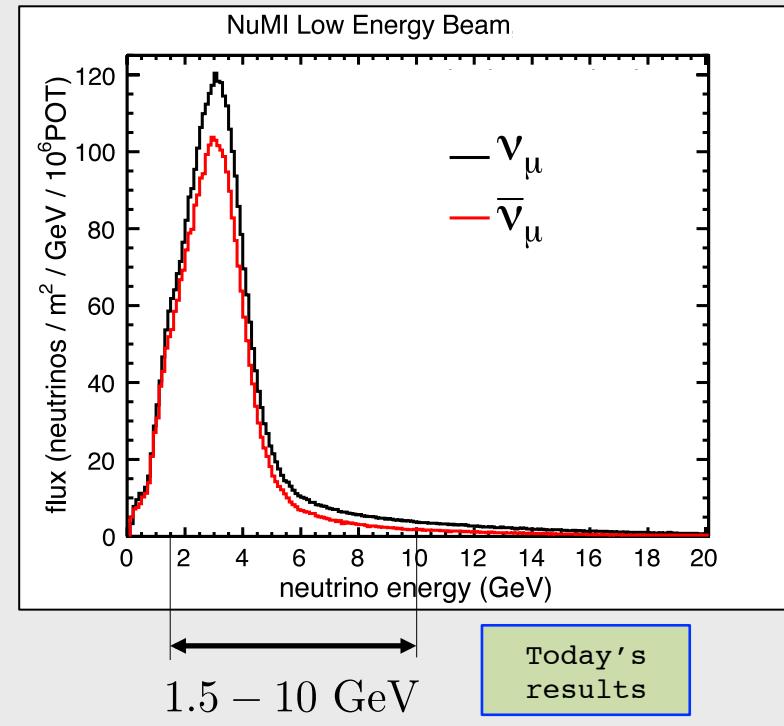
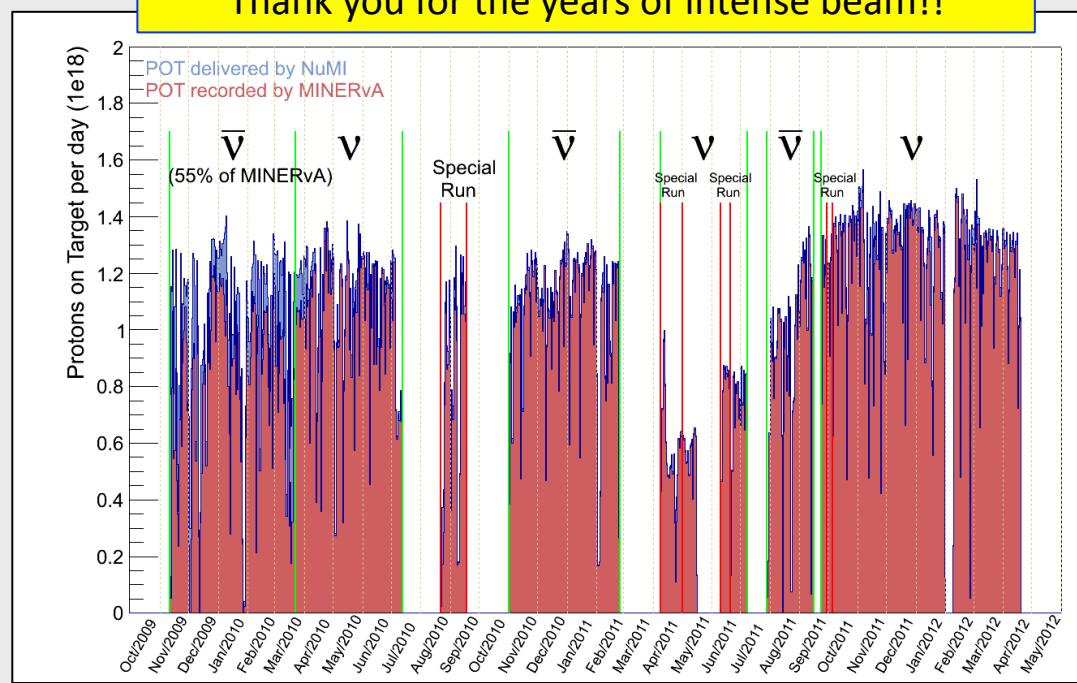
Also: J. Sobczyk arXiv:1201.3673,  
Lalakulich et al. arXiv:1208.3678,  
Nieves et al. arXiv:1204.5404

# The MINERvA Experiment

# The NuMI Beam



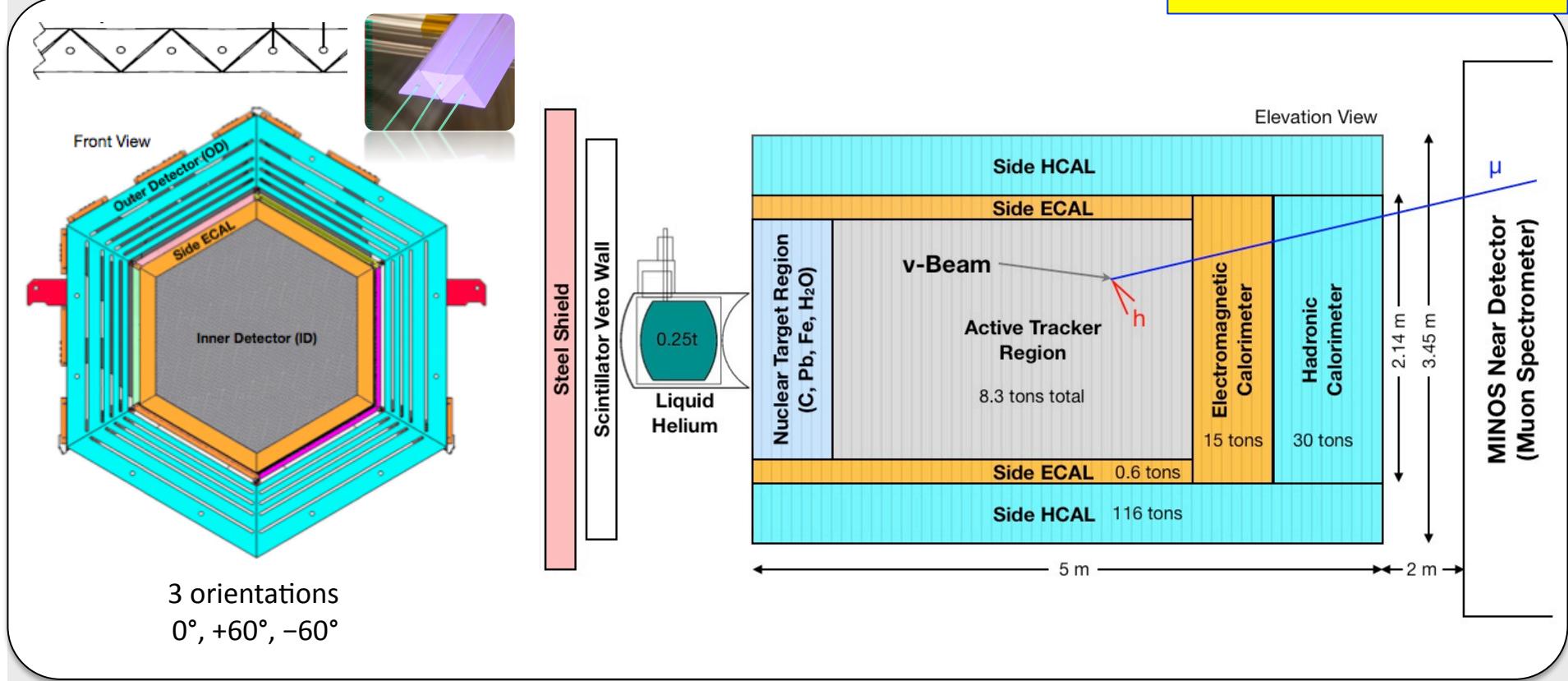
Thank you for the years of intense beam!!





# MINERvA

Thank you to MINOS for the generous sharing of their Near Detector data!!



Detector comprised of **120 “modules”** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

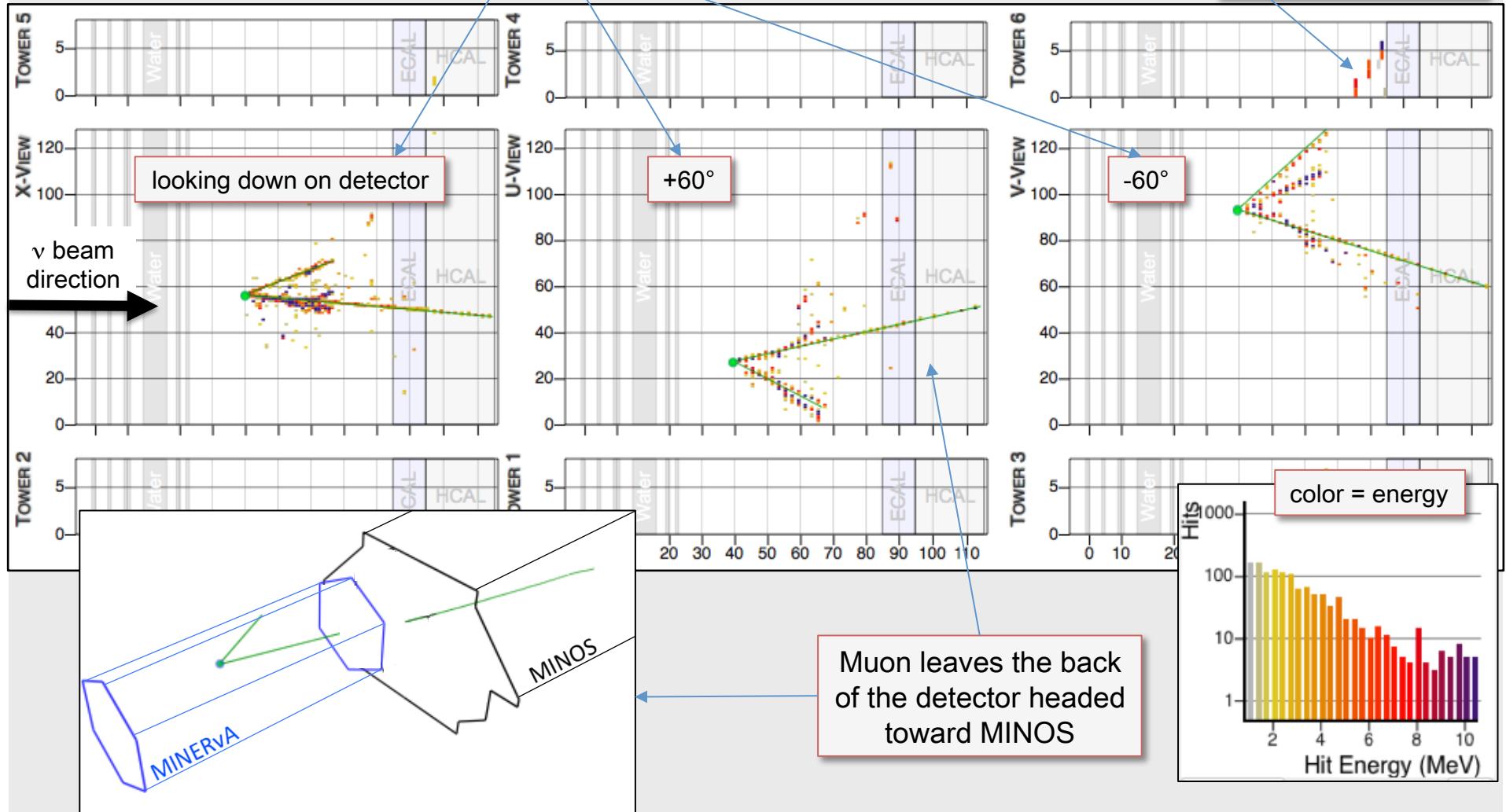
~32k plastic scintillator strip channels total



# MINERvA

Particle leaves the inner detector, stops in outer iron calorimeter

3 stereo views, X—U—V, shown separately





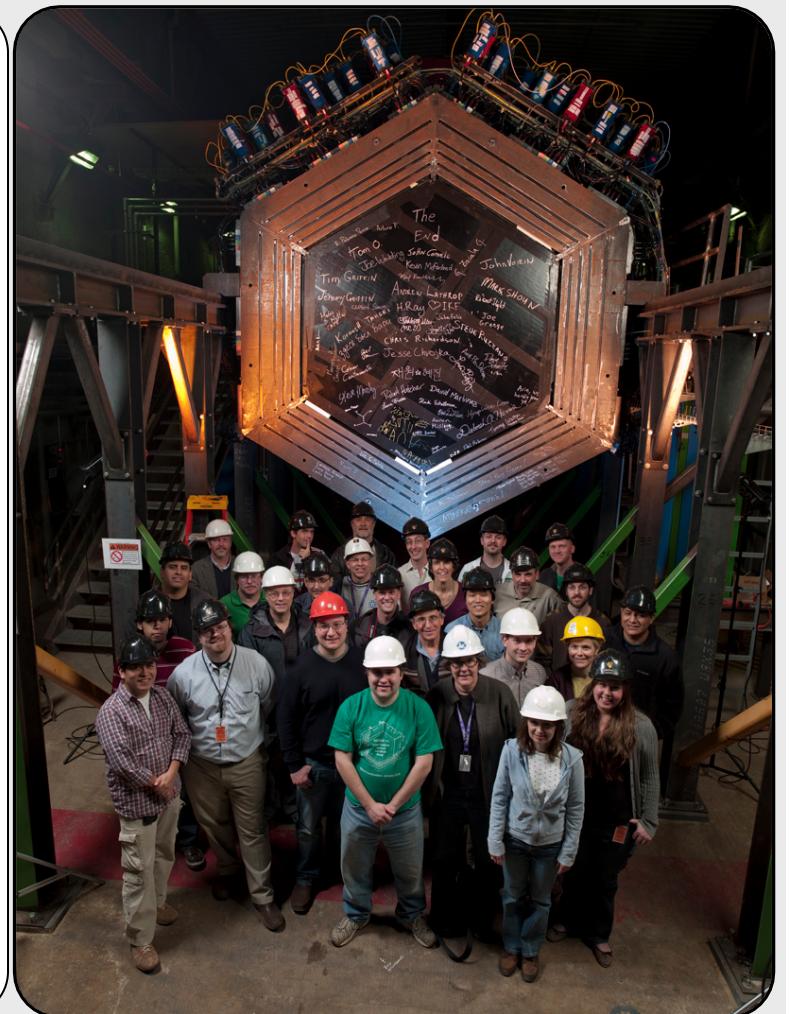
# MINERvA

## More than just a detector...

~80 collaborators from particle and nuclear physics

University of Athens  
University of Texas at Austin  
Centro Brasileiro de Pesquisas Físicas  
Fermilab  
University of Florida  
Université de Genève  
Universidad de Guanajuato  
Hampton University  
Inst. Nucl. Reas. Moscow  
Mass. Col. Lib. Arts  
Northwestern University  
University of Chicago

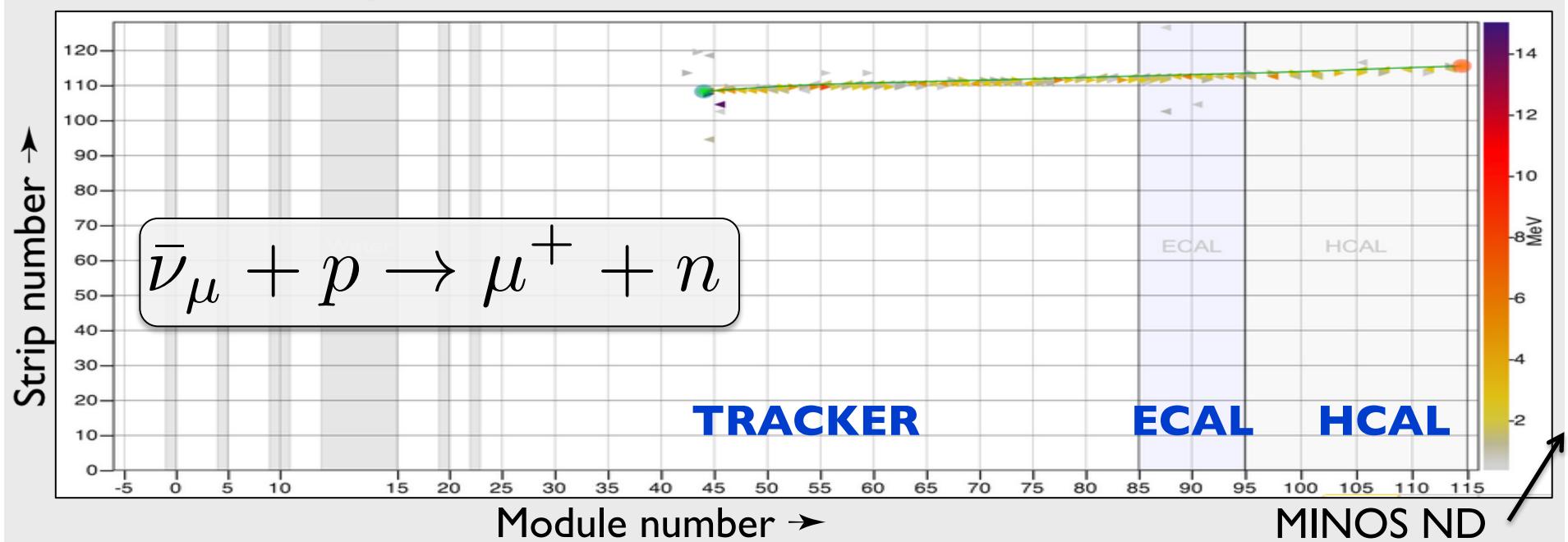
Otterbein University  
Pontificia Universidad Católica del Perú  
University of Pittsburgh  
University of Rochester  
Rutgers University  
Tufts University  
University of California at Irvine  
University of Minnesota at Duluth  
Universidad Nacional de Ingeniería  
Universidad Técnica Federico Santa María  
William and Mary



# Isolating QE Events

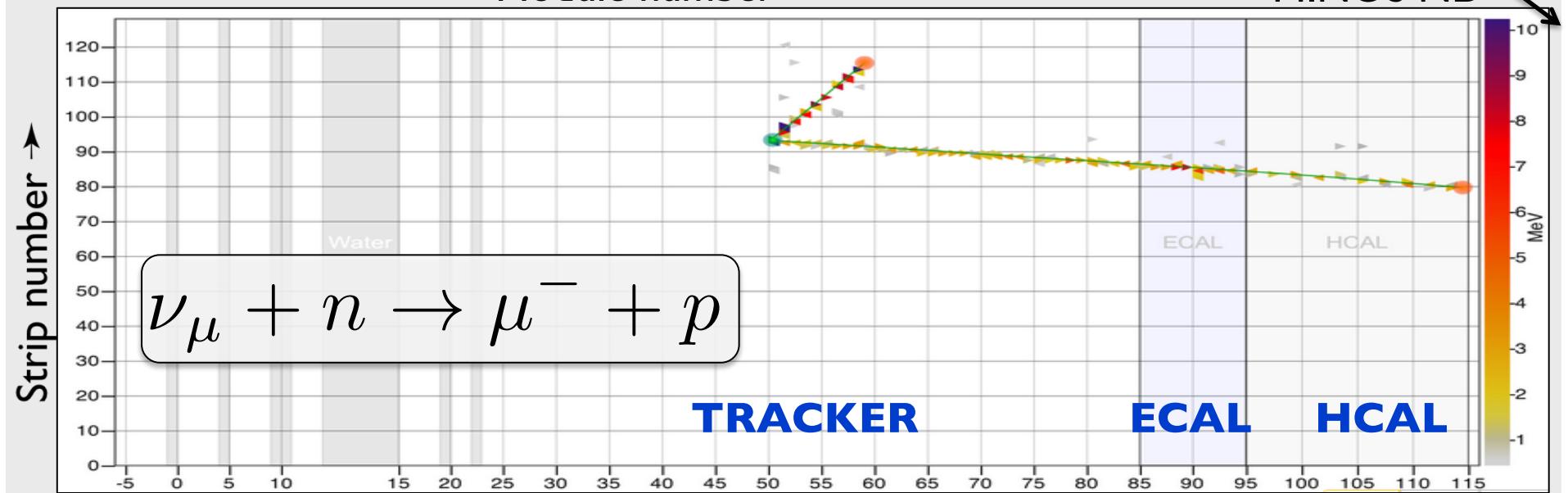
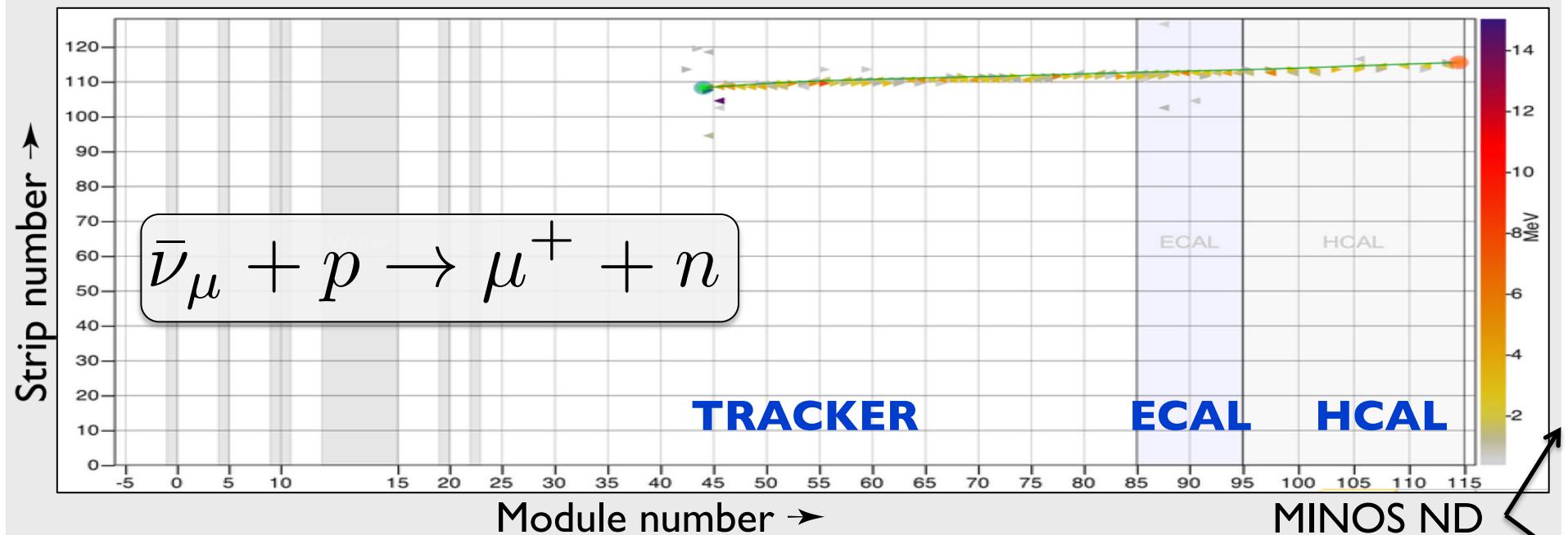
$\nu$  Beam 

MeV



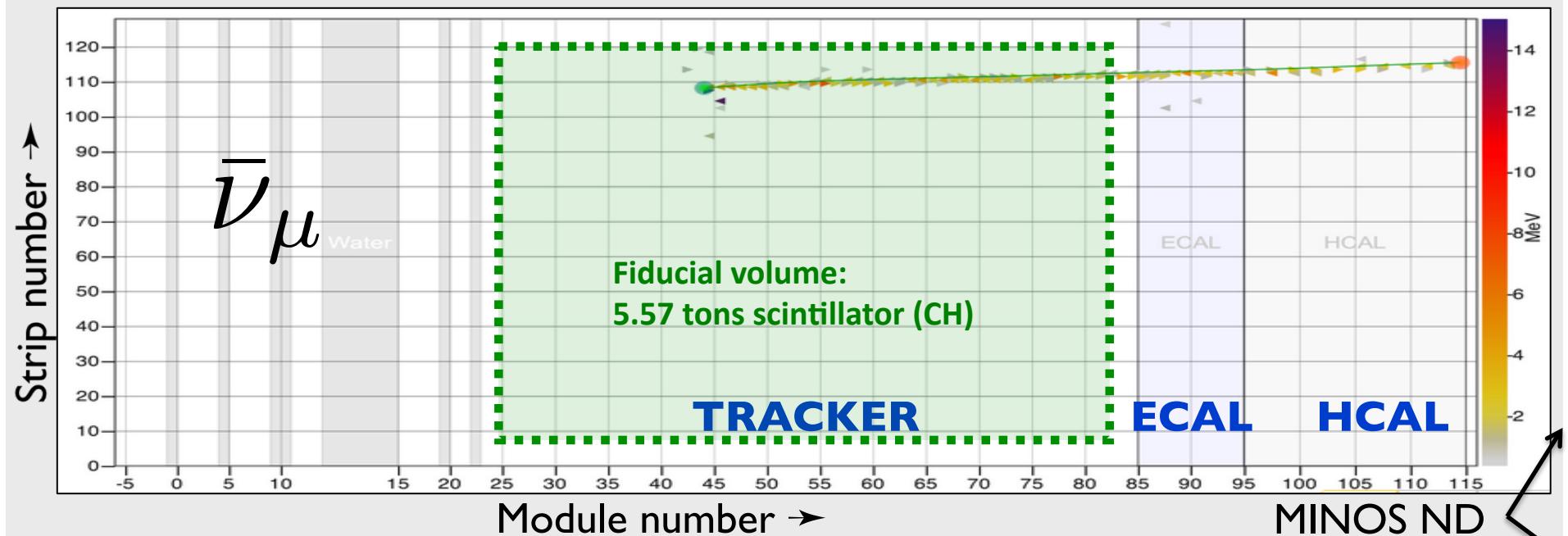
$\nu$  Beam 

MeV



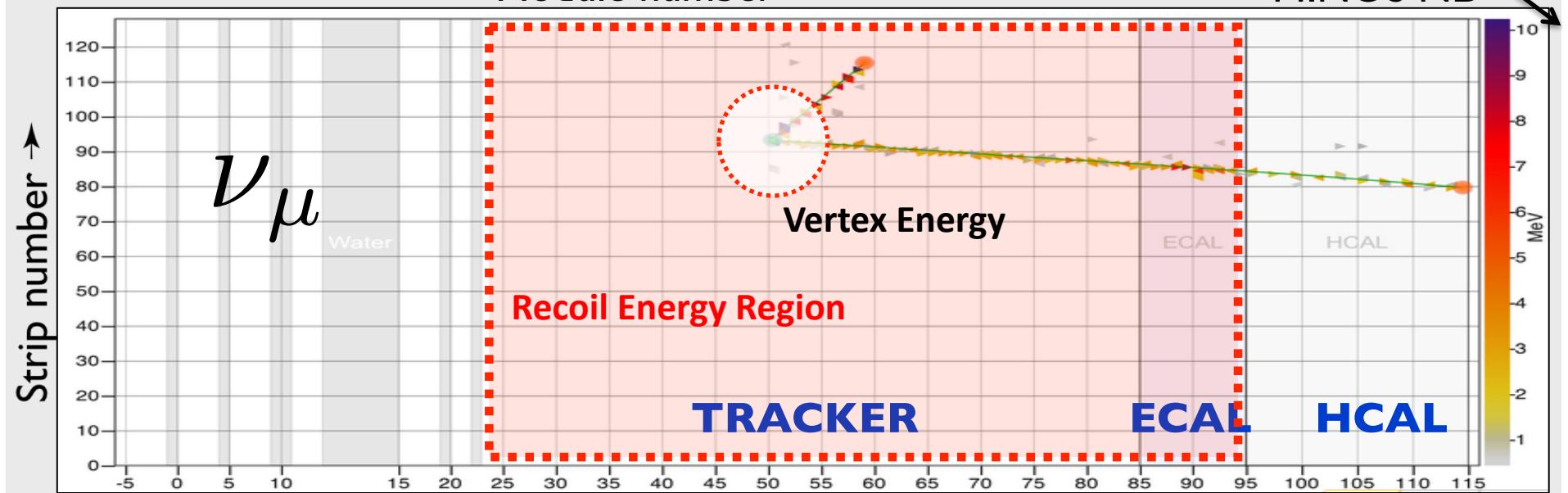
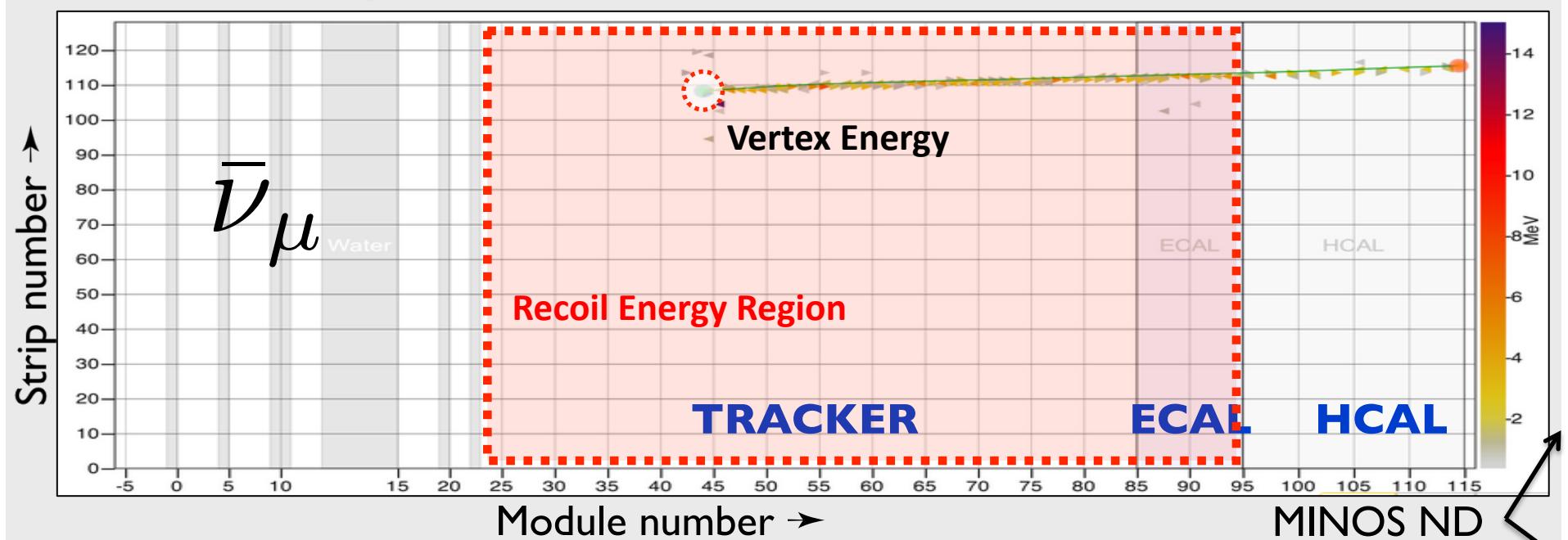
$\nu$  Beam →

MeV



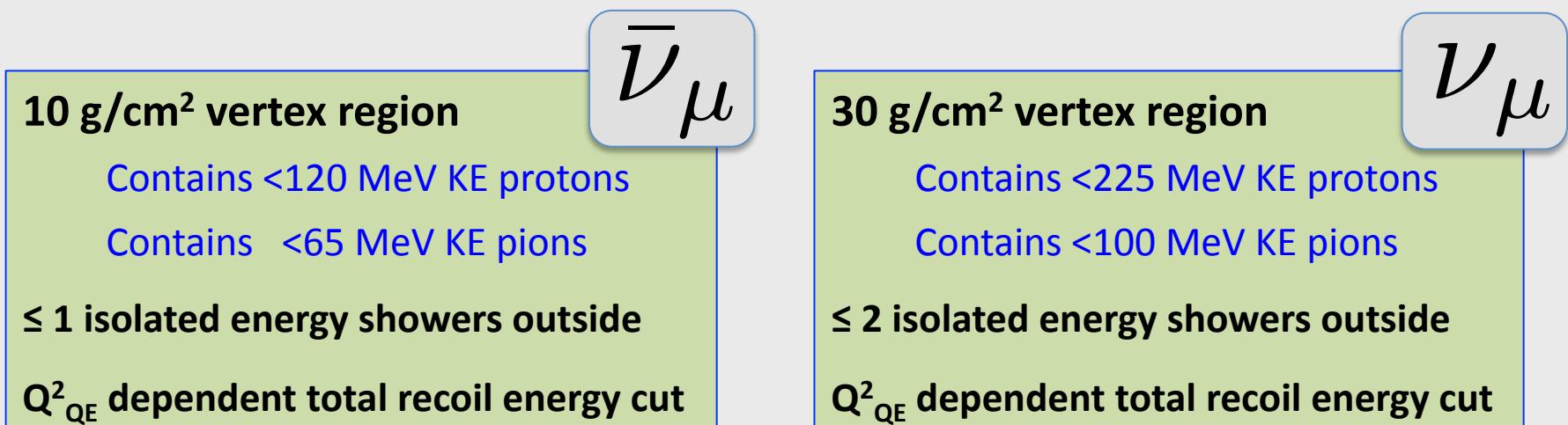
$\nu$  Beam →

MeV



# QE Event Selection

1. Muon track matched to MINOS track, *momentum and charge analyzed*
  - $\mu^+$  for antineutrino
  - $\mu^-$  for neutrino
2. Recoil energy is summed in the tracker and ECAL *excluding a region immediately around the interaction vertex* (determined by the muon track)
  - This excluded region limits sensitivity to the modeling of low energy hadrons produced in the interaction (particularly from multi-nucleon effects)



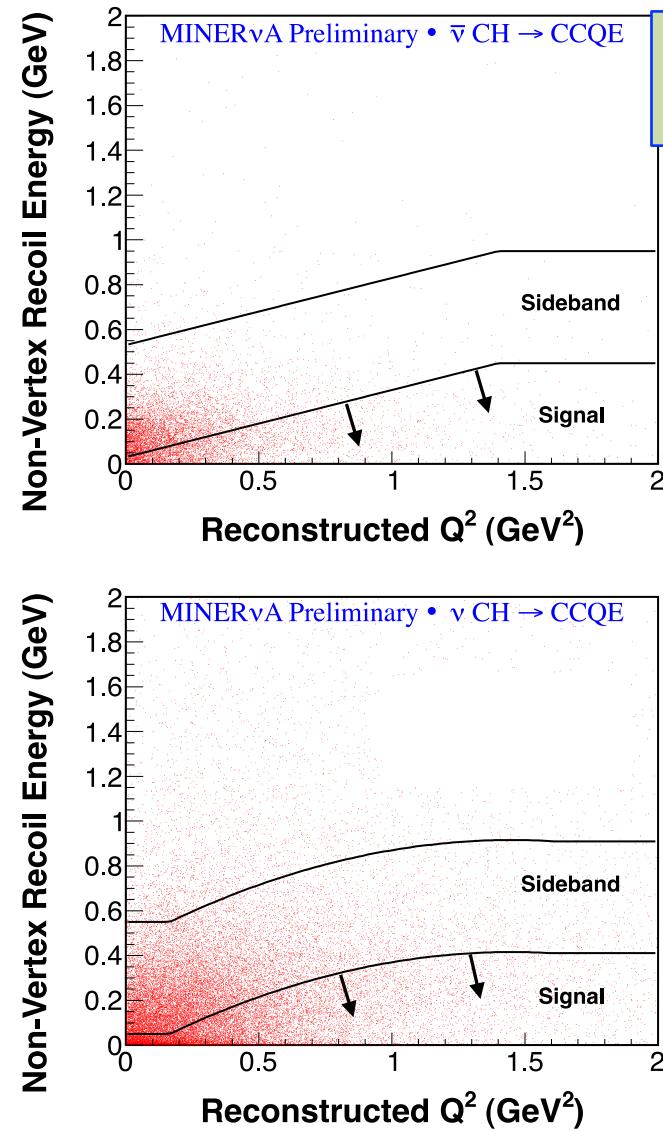
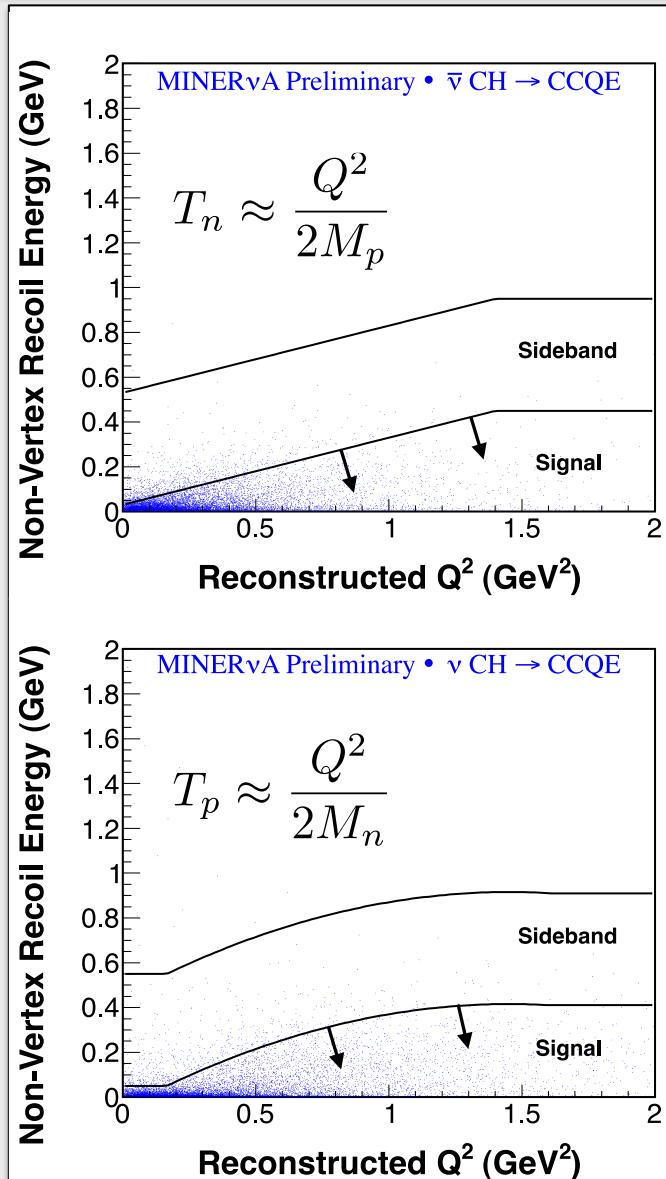
# Recoil Energy

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left( E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

$\bar{\nu}_\mu$

QE

$\nu_\mu$

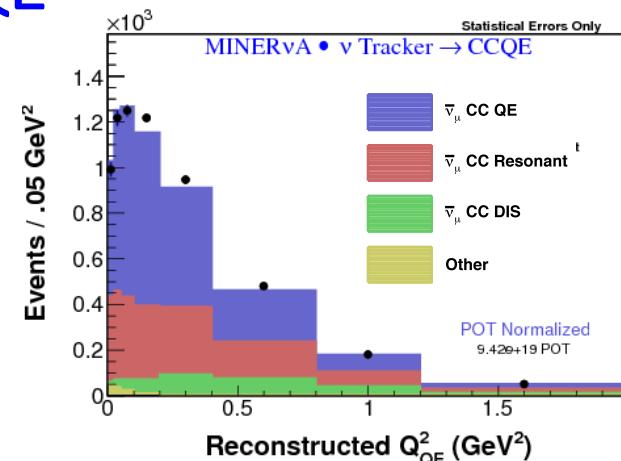
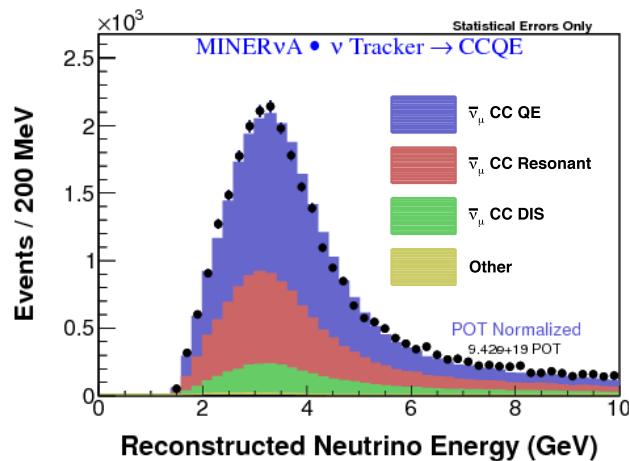
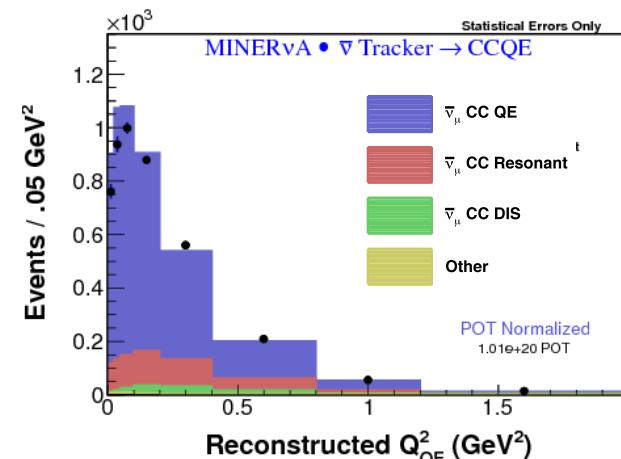
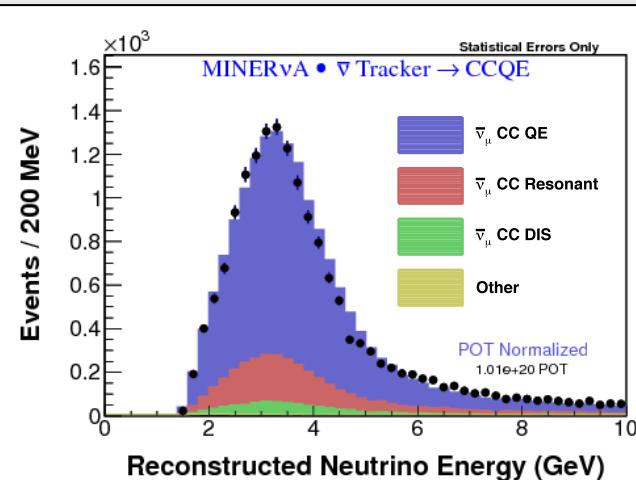


# QE Event Candidates

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2 \cos \theta_\mu}]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left( E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

$$\frac{d\sigma}{dQ_{QE}^2}$$



$\bar{\nu}_\mu$

16,467 events  
54% eff.  
77% purity

$\nu_\mu$

29,620 events  
47% eff.  
49% purity

# Systematic Uncertainties

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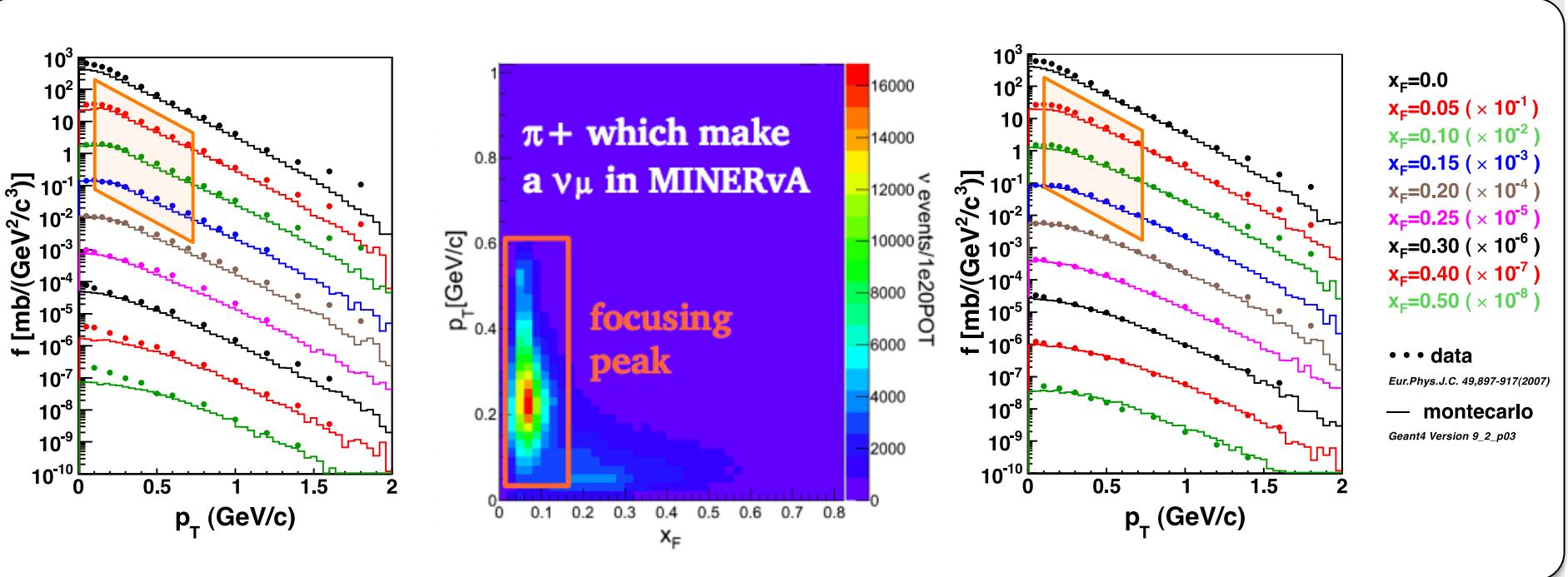
1. Neutrino fluxes
2. Muon reconstruction
3. Recoil reconstruction
4. Primary interaction models
5. Final state interactions

# 1. Neutrino Fluxes

$$p(158 \text{ GeV}) + C \rightarrow \pi^+$$

NA49: Eur.Phys.J C49, 897-917 (2007)

$$p(158 \text{ GeV}) + C \rightarrow \pi^-$$



- Monte Carlo reweighted to match measured  $\pi^+$   $\pi^-$  production cross-sections by NA49. Uncertainties from NA49 cross sections propagated directly to flux.
- Use scaling laws to constrain p+C interactions down to 12 GeV proton energy
  - Method tested by scaling to pion production data from NA61 (31 GeV/c) and HARP (12 GeV/c)
- GEANT4 (FTFP\_BERT physics model) used for rest of simulation

# 2. Muon Energy Scale

- All muons used in these analyses are momentum analyzed in MINOS ND
  - By range in the steel or by curvature in the magnetic field

## Muon momentum scale uncertainties

MINOS range: MINOS NIM A 596, 190 (2008)

$\pm 2\%$  for all  $p_\mu$

MINOS curvature:

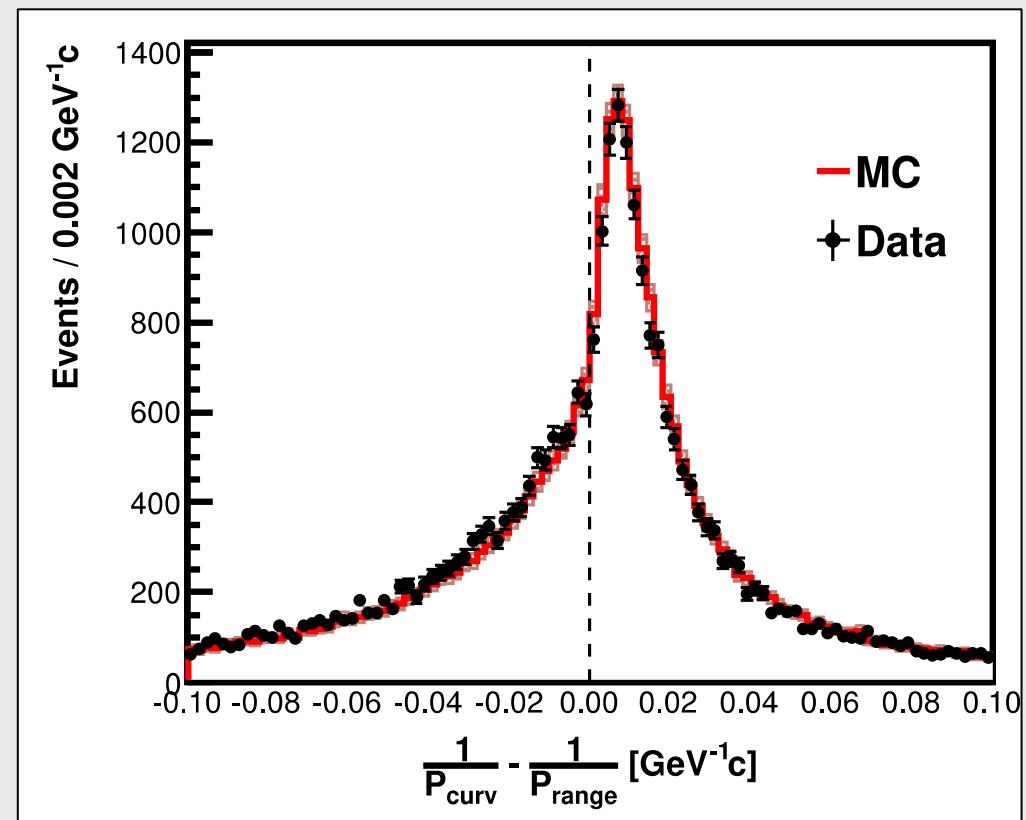
$\pm 2.1\%$  for  $p_\mu < 1.0 \text{ GeV}/c$

$\pm 3.3\%$  for  $p_\mu > 1.0 \text{ GeV}/c$

MINERvA

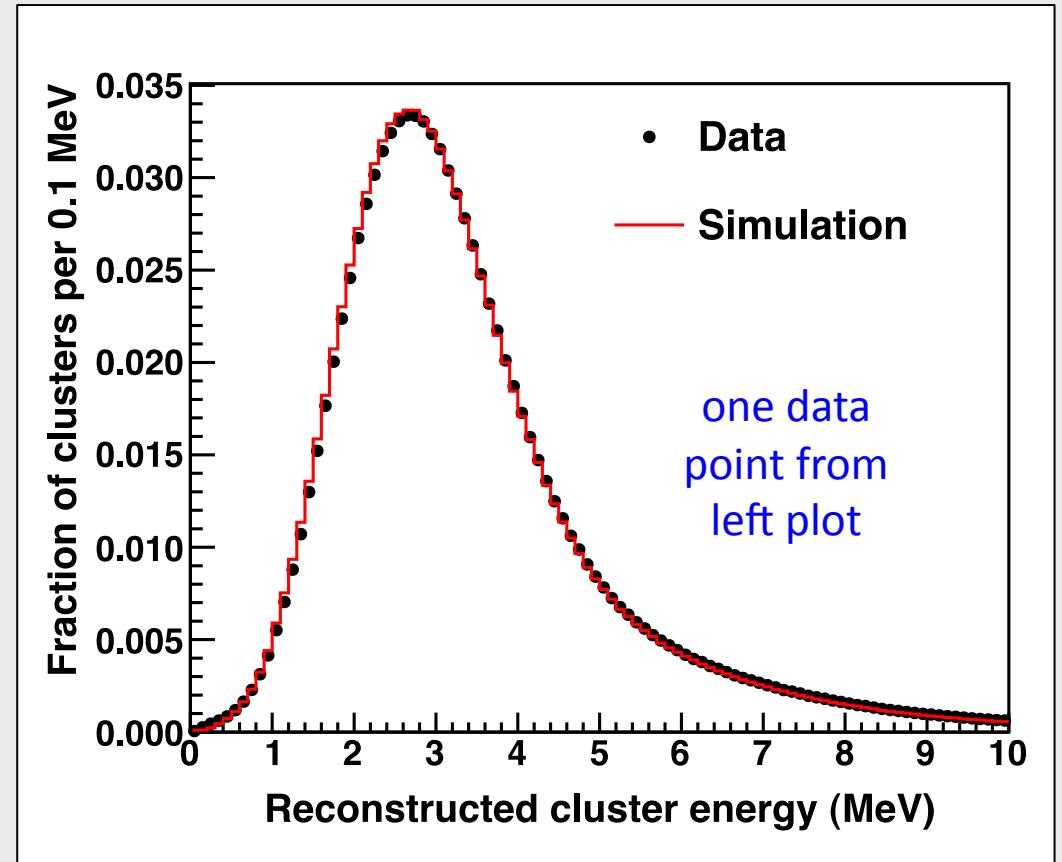
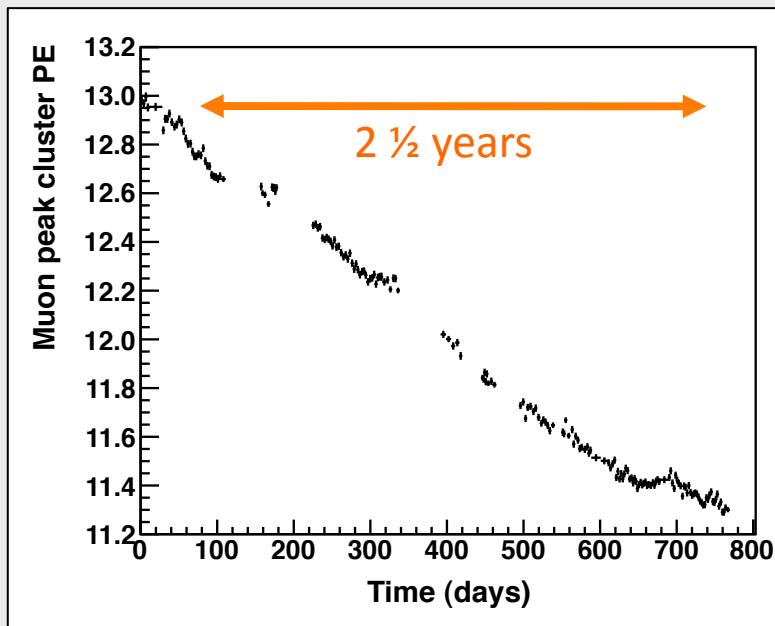
$\pm 11 \text{ MeV}$  (mass model)

$\pm 30 \text{ MeV}$  ( $dE/dx$ )



# 3. Recoil Energy Scale

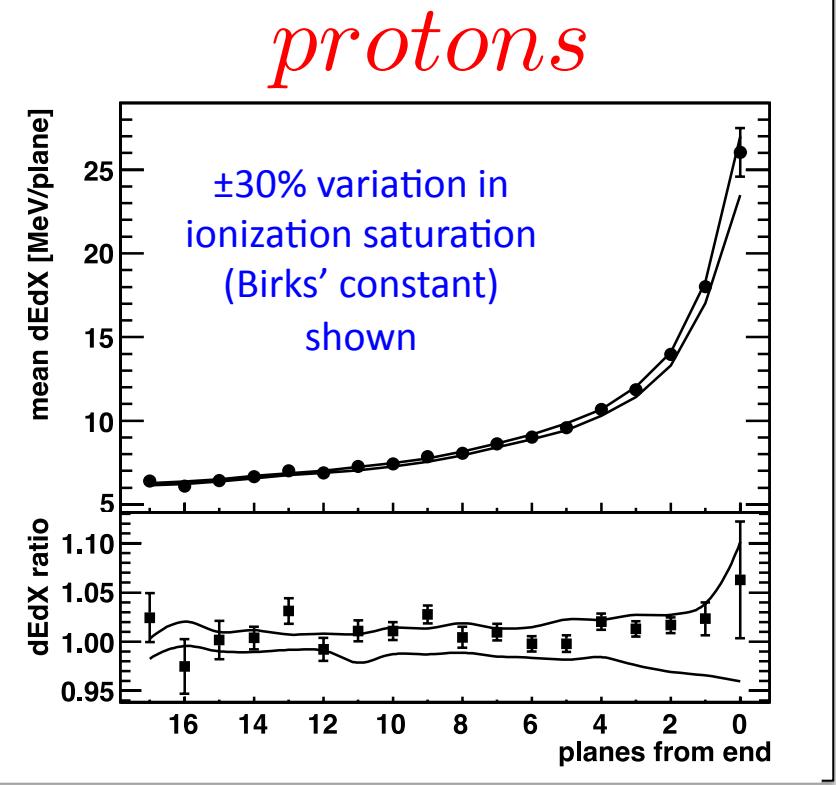
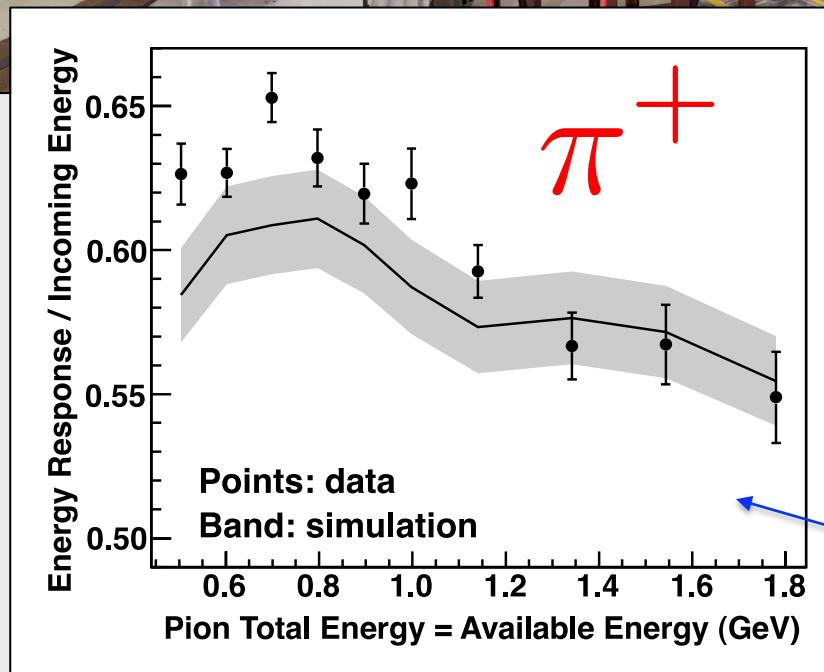
High statistics monitoring of the detector energy response with  
**"Rock Muons"**



1 – 10 MeV mip hits

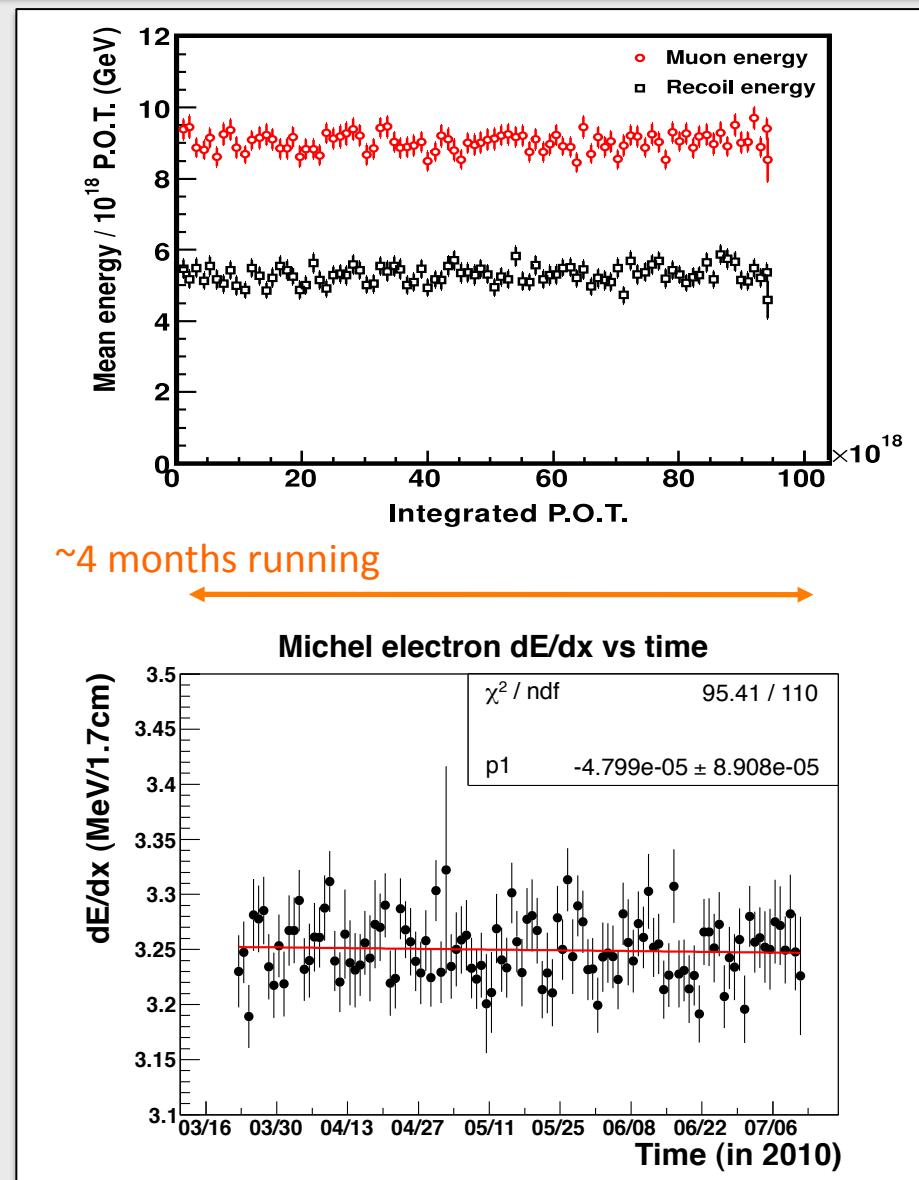
# 3. Recoil Energy Scale

Thank you everyone at MTest Facility!!



high-energy charged  
pion response  
uncertainty  $\approx 5\%$

# 3. Recoil Energy Scale



Muons

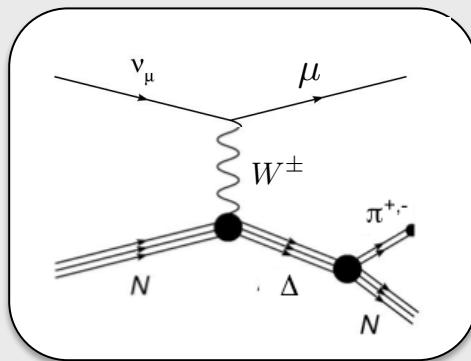
Recoil

Calibrated detector  
**very stable**  
at high and low  
energy scales

Electron  
dE/dx

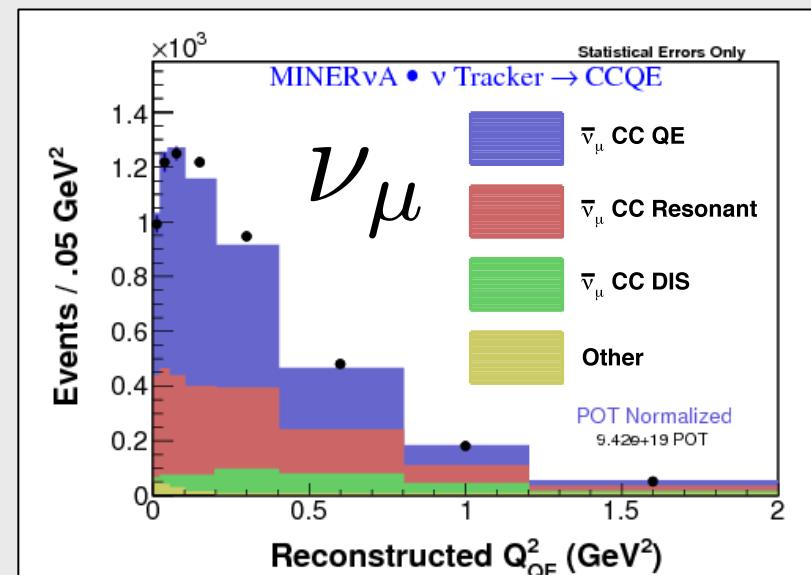
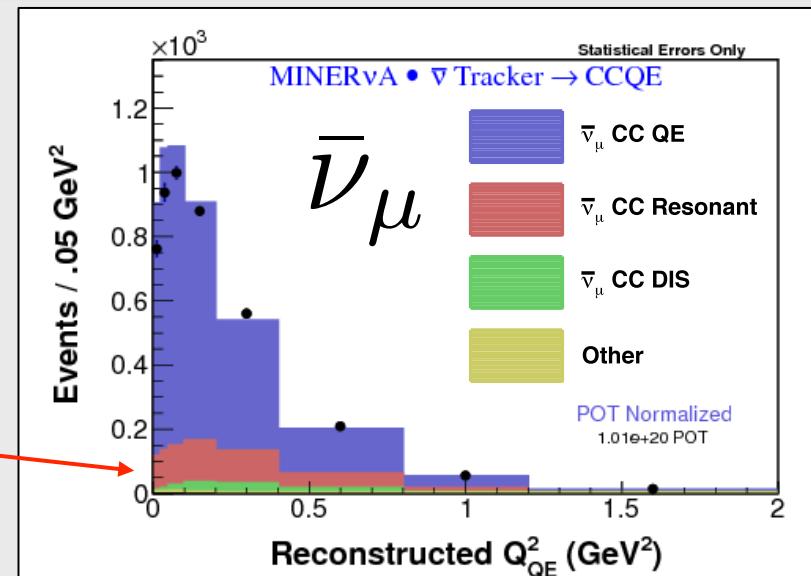
# 4. Primary Interaction Model

GENIE  
2.6.2



- Main background from resonance production and decay to charged pions
  - Pion not tagged by recoil energy cut, OR
  - Pion absorbed in nucleus
- Rate constrained with data

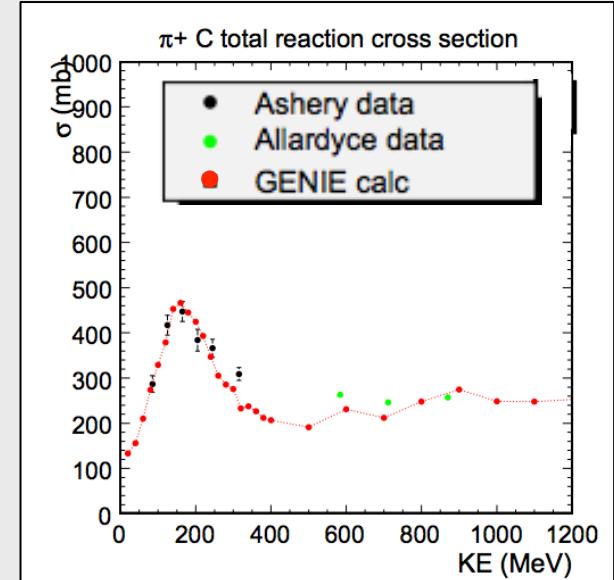
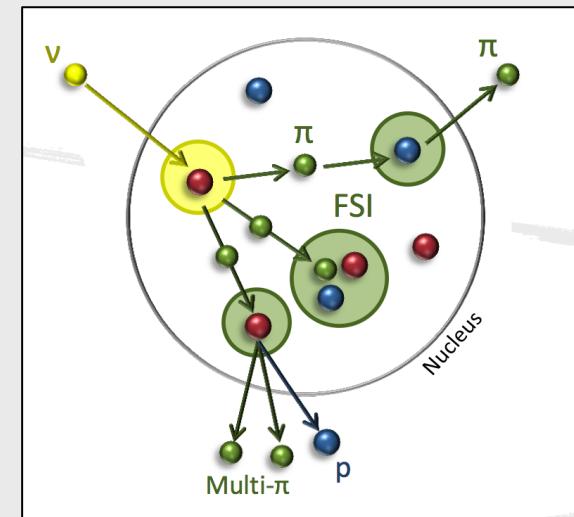
Model parameter	uncertainty
CC resonance prod. normalization	$\pm 20\%$
Resonance model parameter ( $M_A$ )	$\pm 20\%$
Non-resonance pion production	$\pm 50\%$



# 5. Final State Interactions

- Another way the nuclear environment really complicates things
  - Final state different from interaction vertex
- Important part of neutrino event generators
  - Tune with external hadron data
  - Data comparisons inform systematics
- Crucial piece of any analysis

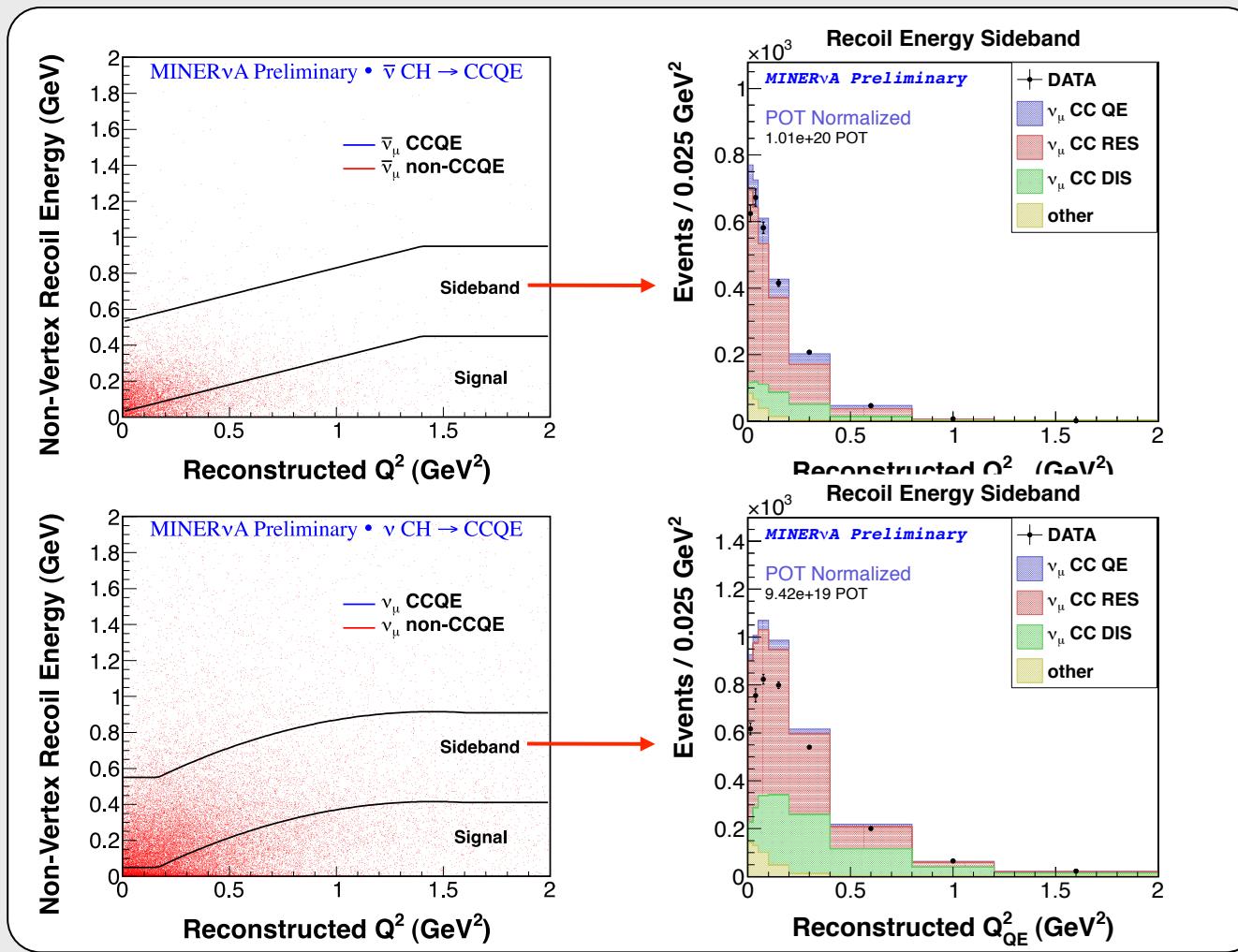
Model parameter	uncertainty
pion/nucleon mean path	$\pm 20\%$
pion/nucleon charge exchange	$\pm 50\%$
pion absorbtion	$\pm 30\%$
pion/nucleon inelastic cross-section	$\pm 40\%$
elastic cross sections	$\pm 10-30\%$



GENIE Physics Manual

# Constraining Non-QE Backgrounds

- Given the challenge and large uncertainties on cross-section models and especially FSI, *constraining backgrounds with data* is very valuable

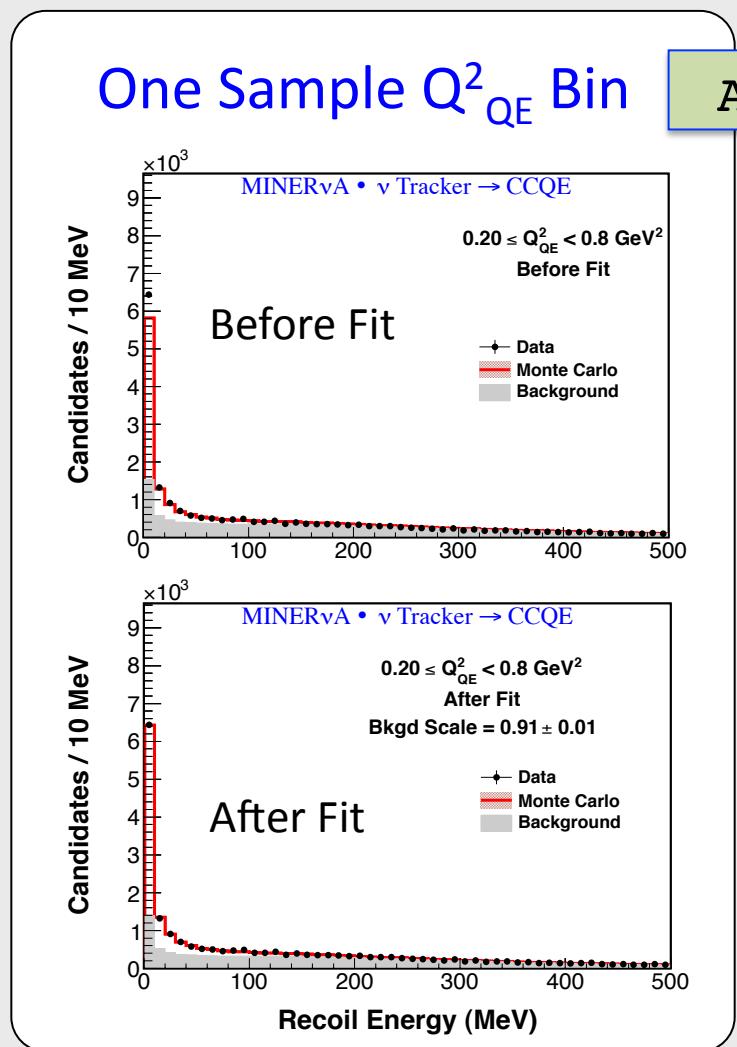


$\bar{\nu}_\mu$

$\nu_\mu$

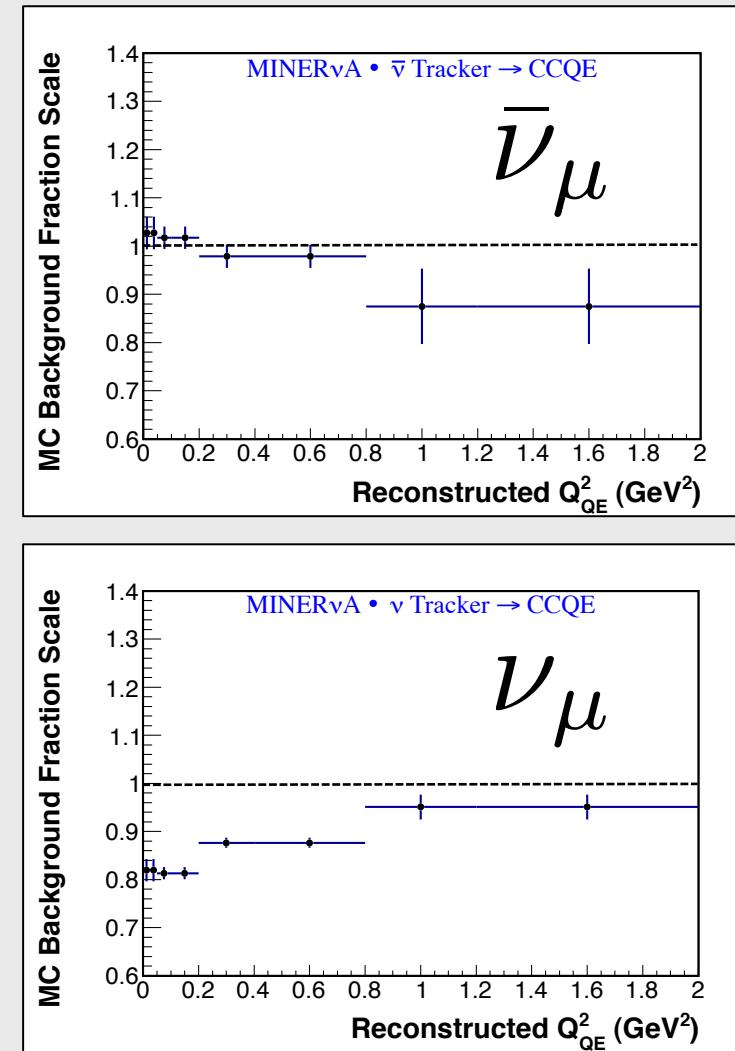
# Constraining Non-QE Backgrounds

- Perform a fit in bins of  $Q^2_{QE}$  to set the relative signal – background fraction

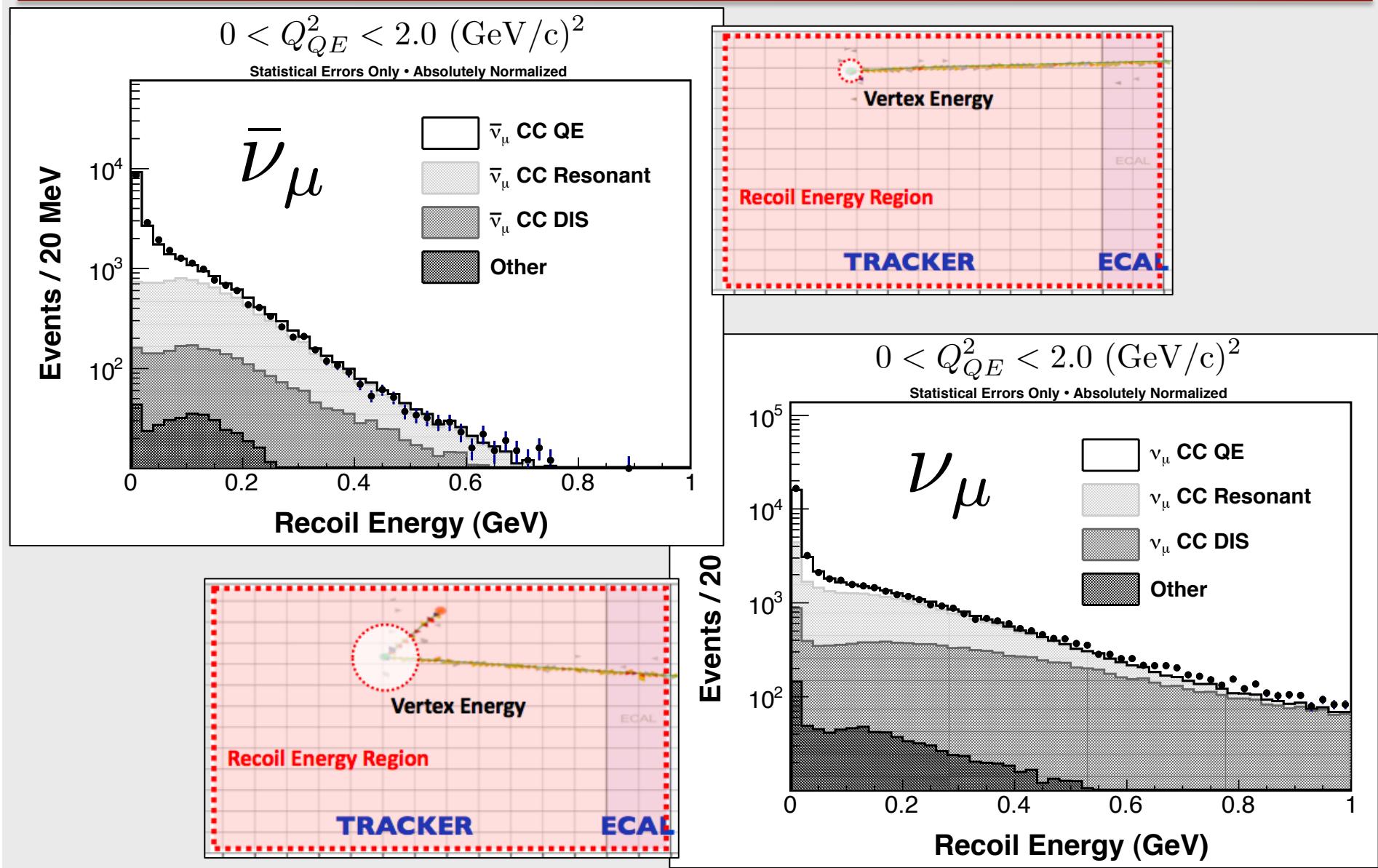


All Bins

Modify the predicted non-QE background rate by 5–15%



# Final Recoil Distributions



# Differential Cross-section

Differential cross-section vs. **4-momentum transfer squared**

**not** to "generator  $Q^2$ "

$Q_{QE}^2 \rightarrow Q_{QE}^2$   
reco  $\mu$       true  $\mu$   
kinematics    kinematics

backgrounds constrained by data

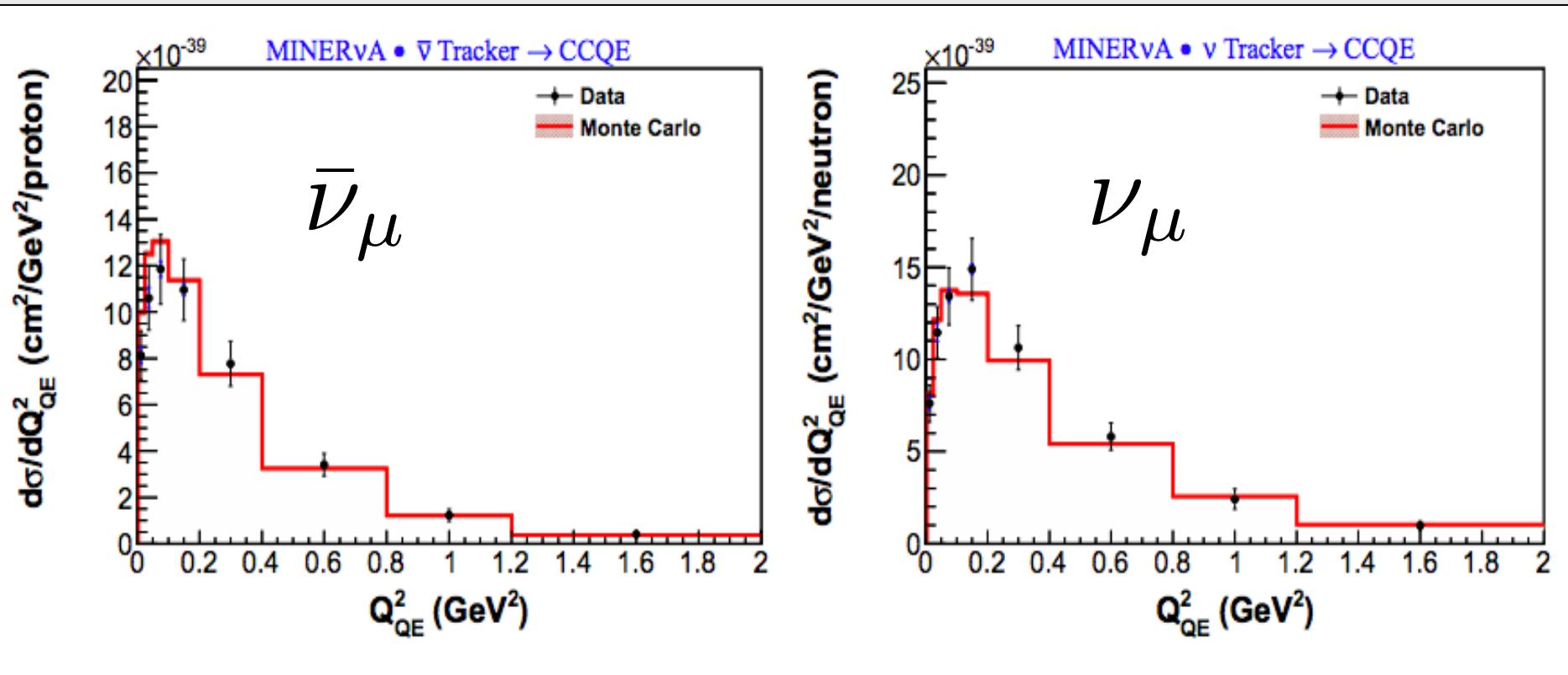
$$\left( \frac{d\sigma}{dQ_{QE}^2} \right)_i = \frac{1}{\Phi T} \frac{1}{\Delta Q_{QE}^2} \frac{\sum_j U_{ij} (N_{data,j} - N_{bg,j})}{\varepsilon_i}$$

flux, targets

bin size

muon eff constrained with data;  
recoil eff uses MC away from vertex

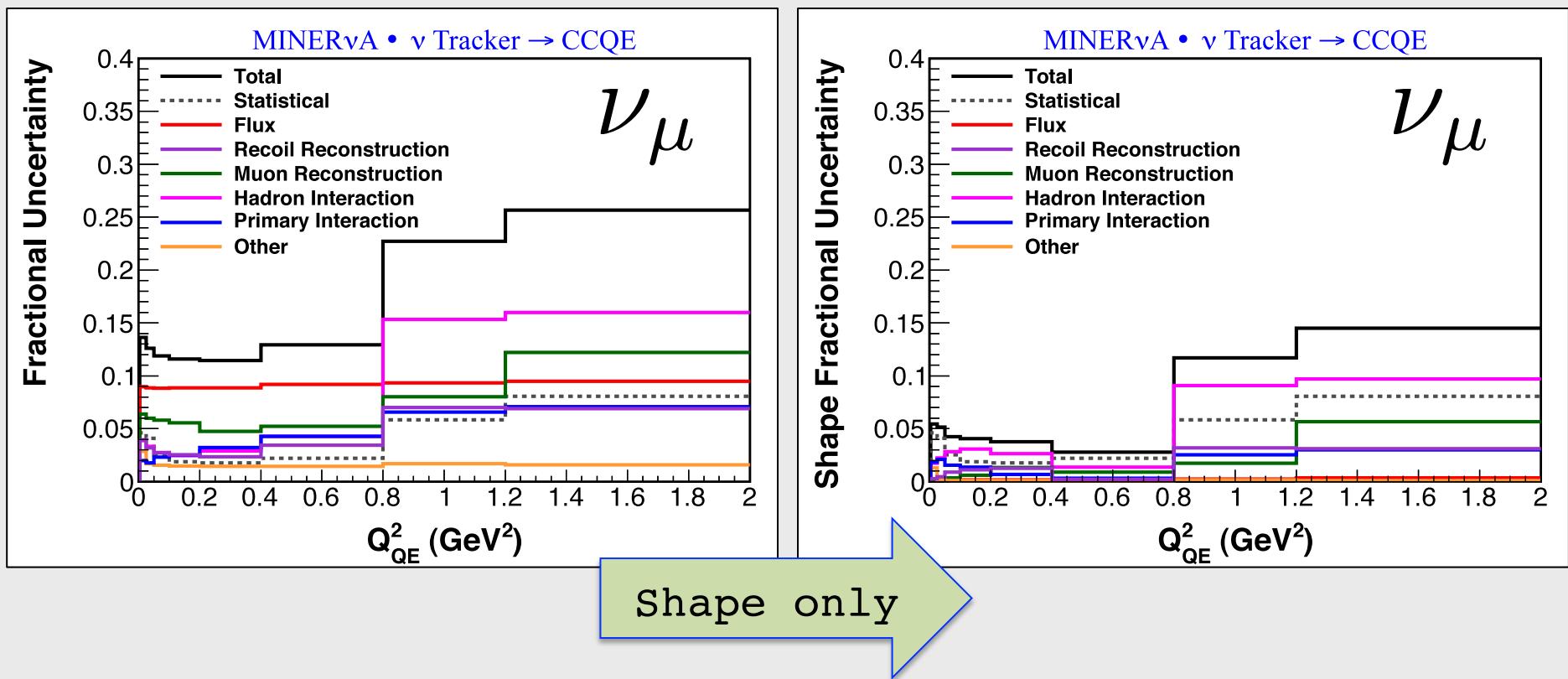
# Differential Cross-Section Results



- To interpret these results, we will focus on two aspects:
  - The shape of the  $d\sigma/dQ^2$  cross-section
  - The amount of energy very near the vertex

# Interpretation #1: $d\sigma/dQ^2$ Shape

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



# Interpretation #1: $d\sigma/dQ^2$ Shape

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- The produced muon kinematics in an event are different if the (anti)neutrino scatters off an *independent quasi-free nucleon* (as assumed in most models) vs. scatters off *multiple nucleons in a correlated state*.
- We do not, therefore, want to use a model to “correct” the  $Q^2_{QE}$  inferred from observed muon kinematics to the “true”  $Q^2$  generated in that model.
- Instead, we are careful to *only correct for detector smearing effects* and how they impact the calculated  $Q^2$  distribution
  - $E_\mu$  and  $\theta_\mu$  smearing only

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - \left[ (M_n - E_B)^2 + m_\mu^2 - M_p^2 \right]}{2 \left[ (M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left( E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$

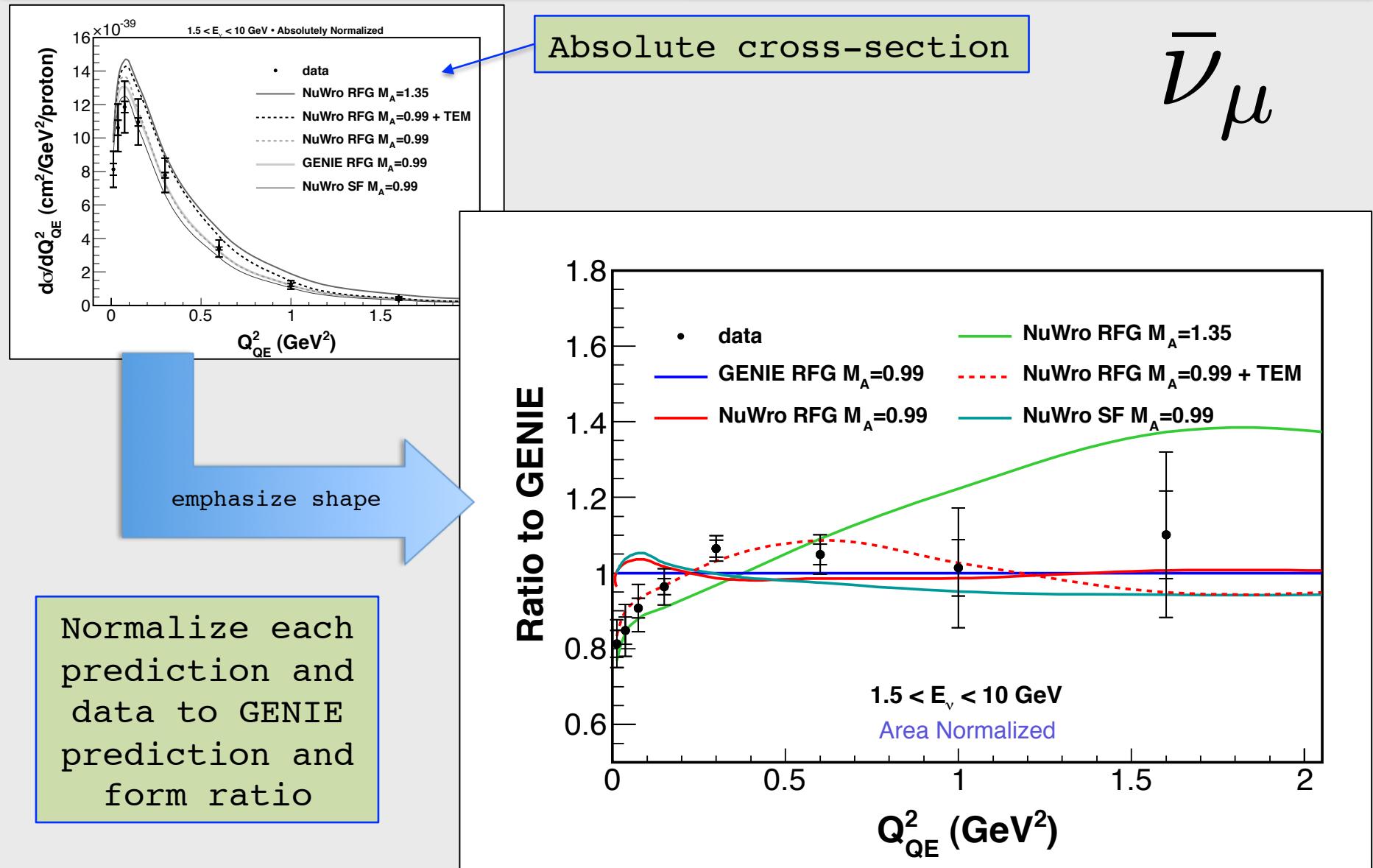
# Interpretation #1: $d\sigma/dQ^2$ Shape

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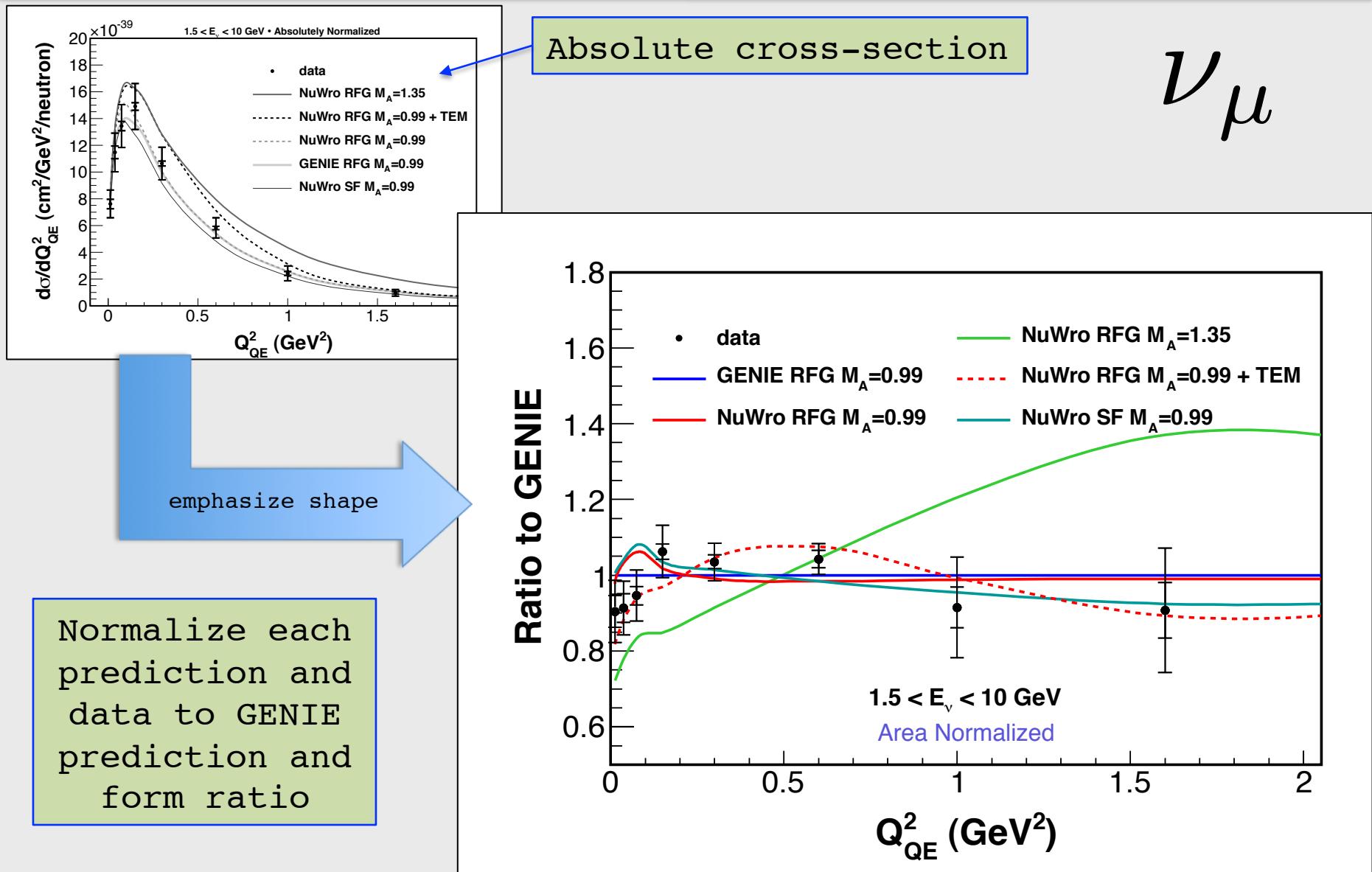
- Models that introduce nuclear correlations of various kinds *tend to modify the QE cross-section as a function of  $Q^2$*  (for a given  $\nu$  energy spectrum)
- The models:
  - Relativistic Fermi Gas (RFG),  $M_A = 0.99 \text{ GeV}/c^2$ 
    - The canonical model in modern event generators used by all neutrino experiments
  - Relativistic Fermi Gas (RFG),  $M_A = 1.35 \text{ GeV}/c^2$ 
    - Motivated by recent measurements where this change was fairly successful at reproducing data
  - Nuclear Spectral Function (SF),  $M_A = 0.99 \text{ GeV}/c^2$ 
    - More realistic model of the nucleon momentum – energy relationship than standard RFG
  - Transverse Enhancement Model (TEM),  $M_A = 0.99 \text{ GeV}/c^2$ 
    - Empirical model which modifies the magnetic form factors of bound nucleons to reproduce an enhancement in the transverse cross-section observed in *electron-nucleus scattering* attributed to the presence of meson exchange currents (MEC) in the nucleus

Bodek, Budd, Christy, Eur. Phys. J. C 71:1726 (2011), arXiv:1106.0340

# $d\sigma/dQ^2$ Shape - Antineutrino



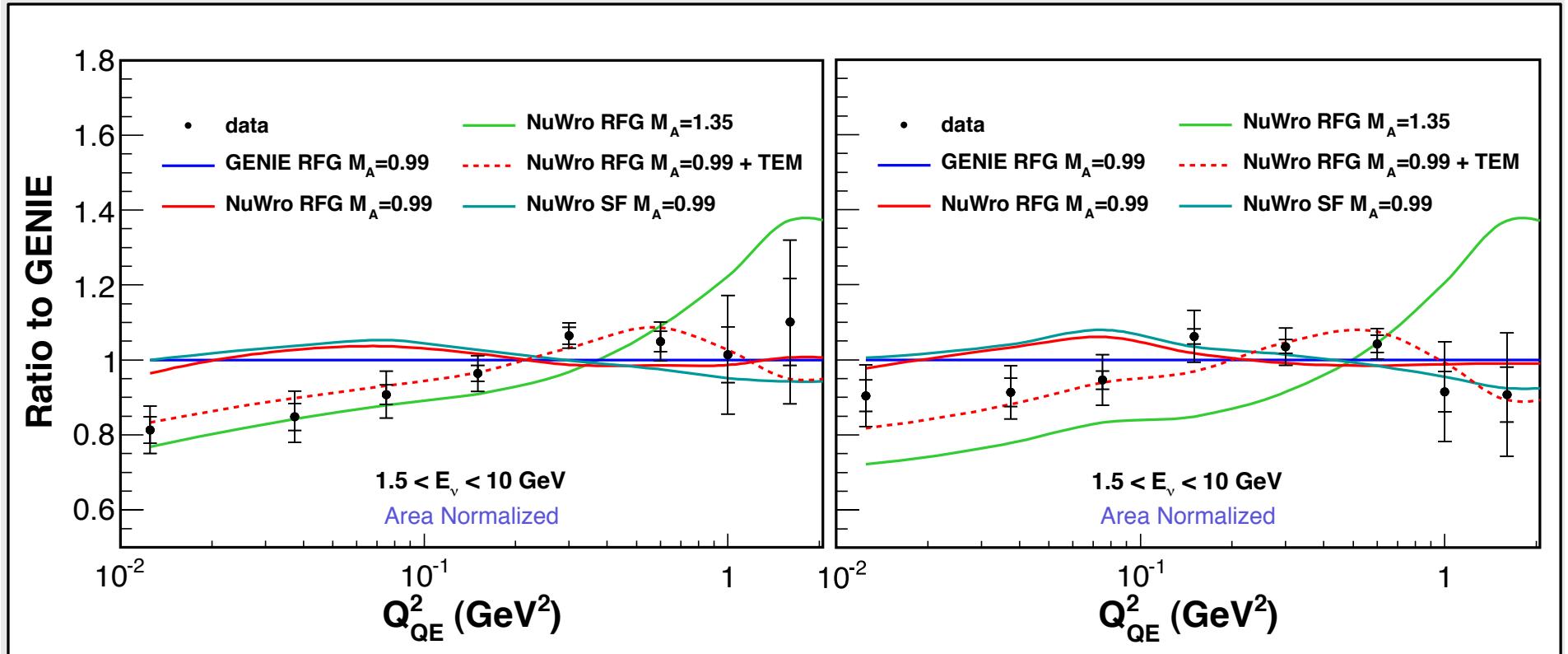
# $d\sigma/dQ^2$ Shape - Neutrino



# $d\sigma/dQ^2$ Shape

$\bar{\nu}_\mu$  CCQE

$\nu_\mu$  CCQE



same plots with log x-axis to see low  $Q^2$  region

# Interpretation #1: $d\sigma/dQ^2$ Shape

- The shape of the measured neutrino and antineutrino  $d\sigma/dQ^2$  cross-sections *disfavor a standard relativistic Fermi gas* implementation for carbon with  $M_A = 0.99 \text{ GeV}/c^2$

$\bar{\nu}_\mu$

NuWro Model	RFG	RFG +TEM	RFG	SF
$M_A$ (GeV)	0.99	0.99	1.35	0.99
Rate $\chi^2/\text{d.o.f.}$	2.64	1.06	2.90	2.14
Shape $\chi^2/\text{d.o.f.}$	2.90	0.66	1.73	2.99

$\nu_\mu$

NuWro Model	RFG	RFG +TEM	RFG	SF
$M_A$ (GeV/ $c^2$ )	0.99	0.99	1.35	0.99
Rate $\chi^2/\text{d.o.f.}$	3.5	2.4	3.7	2.8
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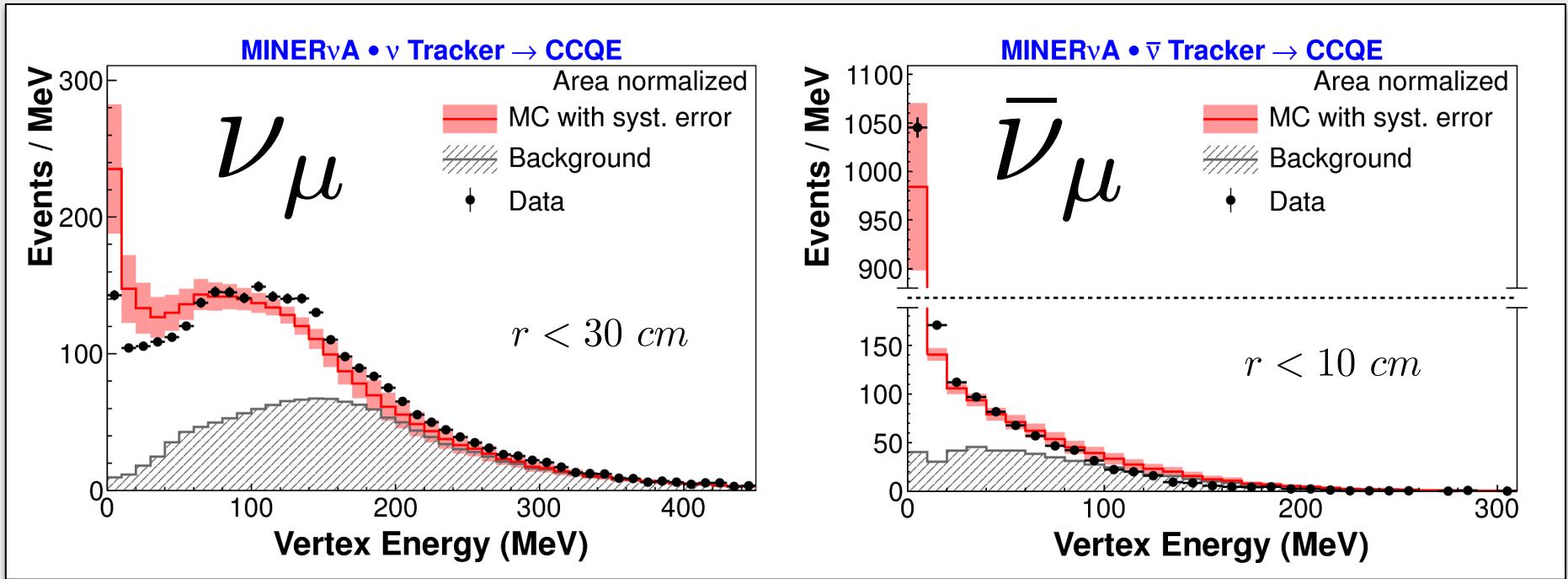
- Changing only the axial-mass  $M_A = 1.35 \text{ GeV}/c^2$  does marginally improve agreement with data
- The data most prefer an empirical model that attempts to transfer the observed *enhancement* in electron-nucleus scattering *attributed to meson exchange current (MEC) contributions* to neutrino-nucleus scattering

# Interpretation #2: Vertex Energy

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- Microscopic models of multi-nucleon (np-nh) contributions are not presently available in event generators at NuMI energies
- No prediction for the hadron kinematics in these classes of events
- In general, *multi-nucleon emission is expected in interactions with correlated nucleons*, so this provides another possible signature
  - Additional nucleons beyond the expected neutron (antineutrino) or proton (neutrino)
- So, we *look very near the interaction vertex* in neutrino and antineutrino events for *excess energy* coming from charged nucleons (protons)
  - Recall, we purposefully avoided this region when selecting QE candidates
    - Because we did not want our QE event selection biased by the MC not having these multi-nucleon events; now we look in the ignored region
  - Final State Interaction (FSI) uncertainties are very important in this analysis

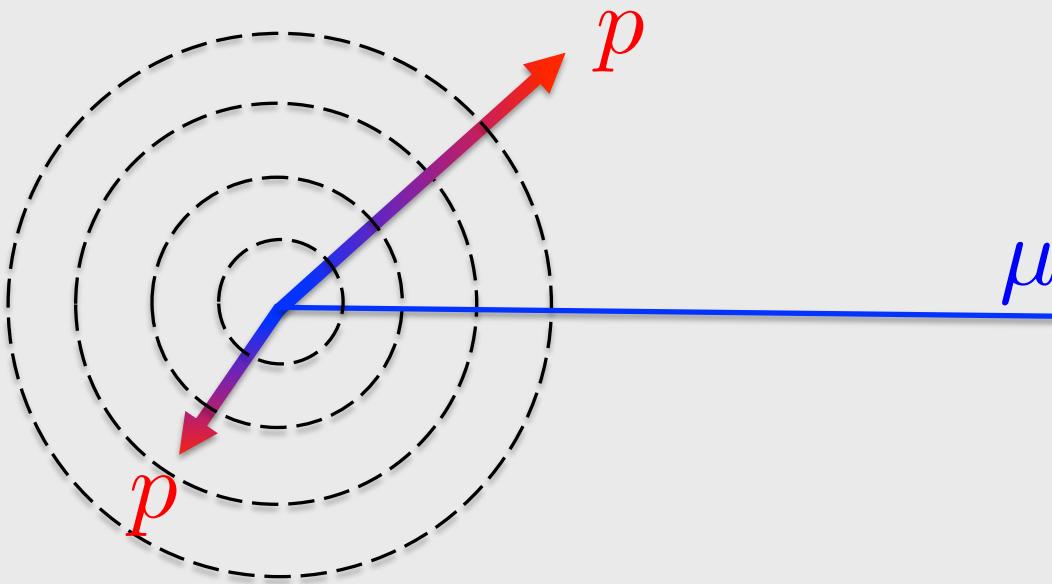
# Vertex Energy



- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the *working assumption* that the additional vertex energy per event in data is *due to protons*

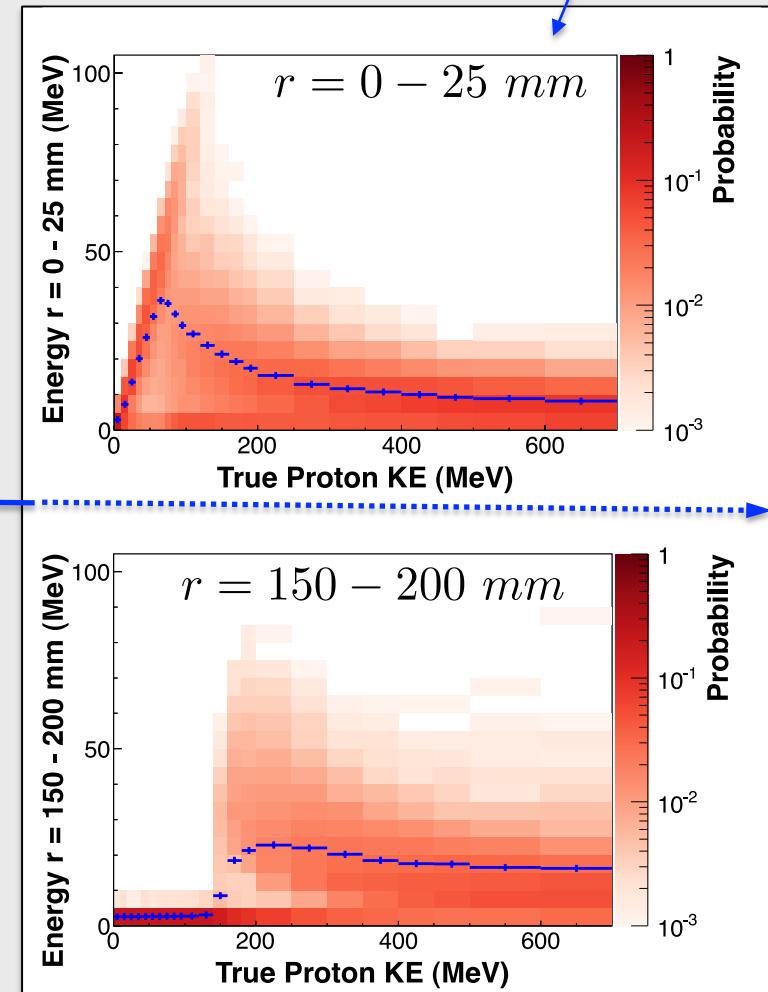
# Vertex Energy

- Examine annular rings around the reconstructed vertex
  - Out to 10 cm for antineutrino ( $\sim 120$  MeV proton)
  - Out to 30 cm for neutrino ( $\sim 225$  MeV proton)

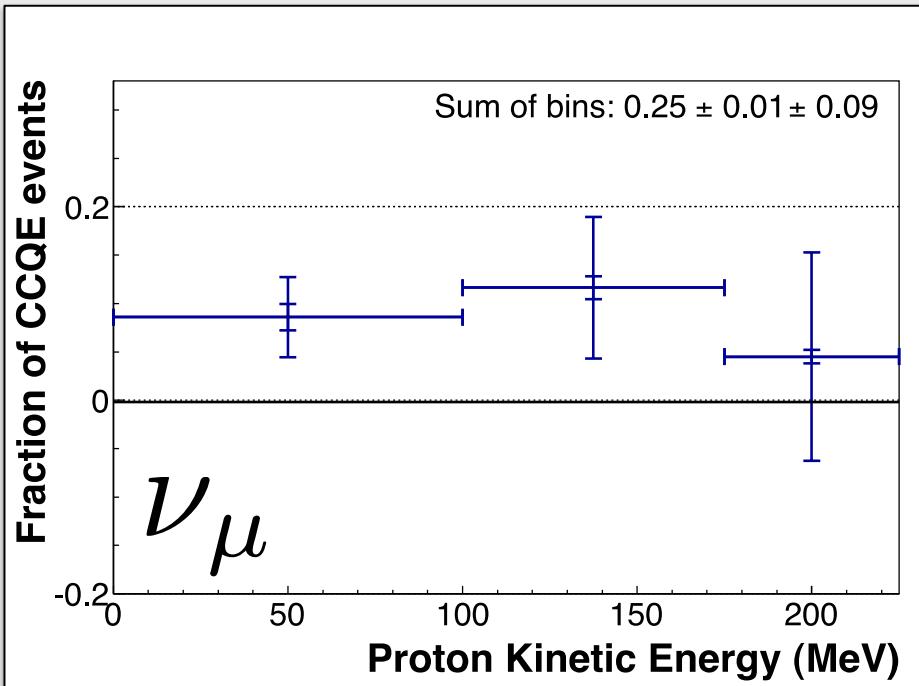


Note: to add visible energy to an inner annulus you must **add a charged hadron**, not just increase energy of an existing one

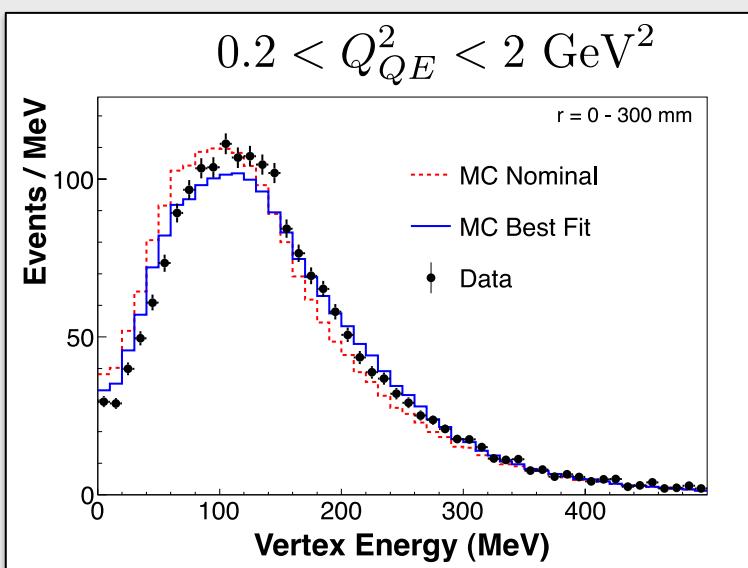
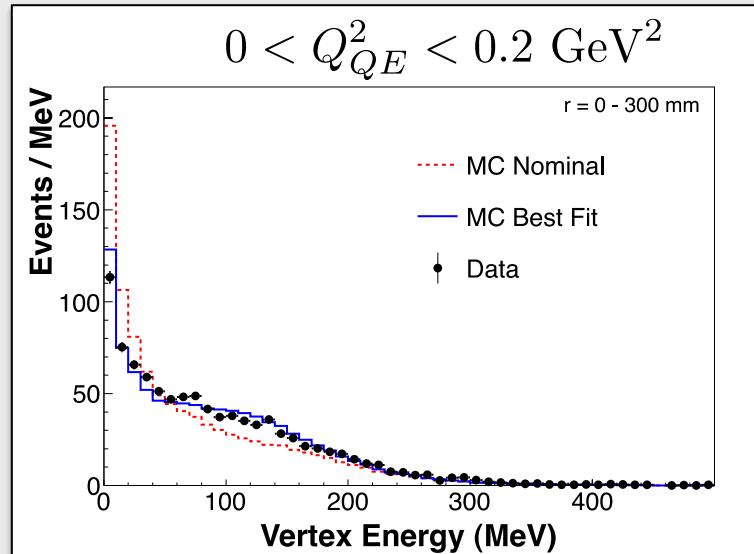
$E_{\text{vis}}$  in that annulus vs. true  $\text{KE}_{\text{proton}}$



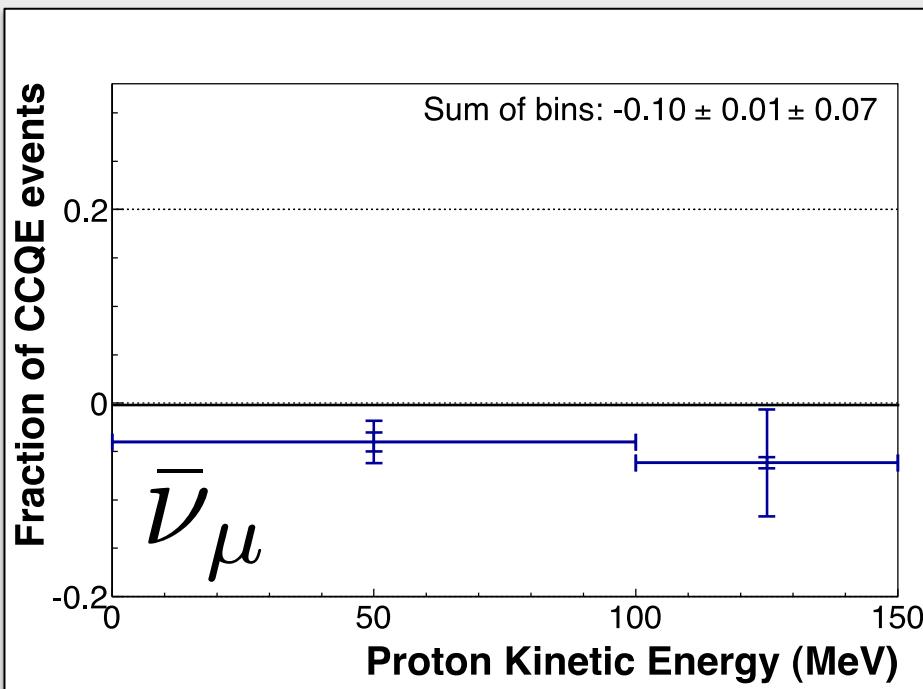
# Vertex Energy - Neutrinos



We find that adding an additional low-energy proton ( $KE < 225$  MeV) to **( $25 \pm 9$ )% of QE events** improves agreements with data

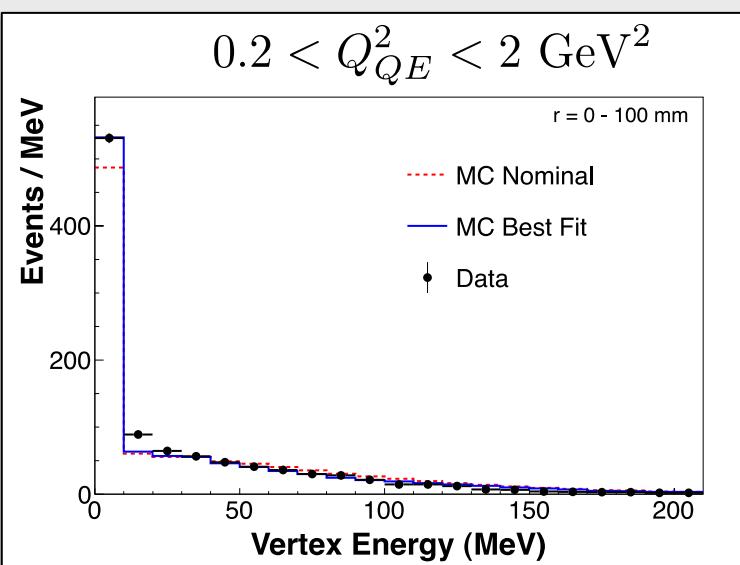
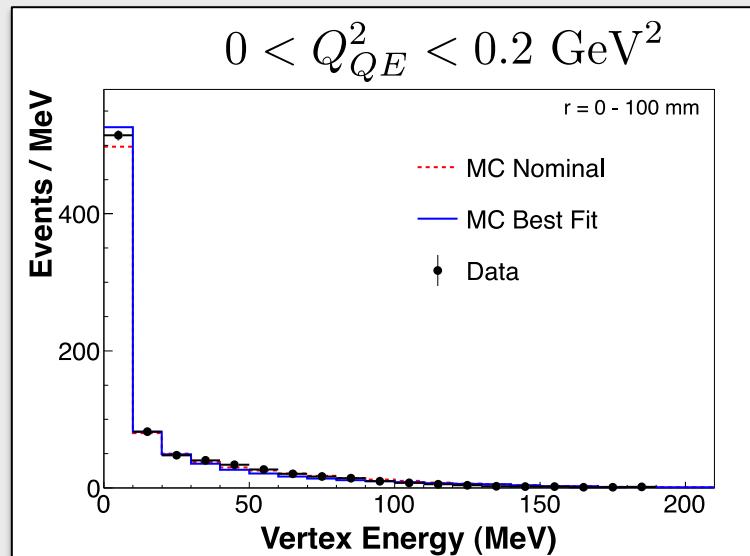


# Vertex Energy - Antineutrinos



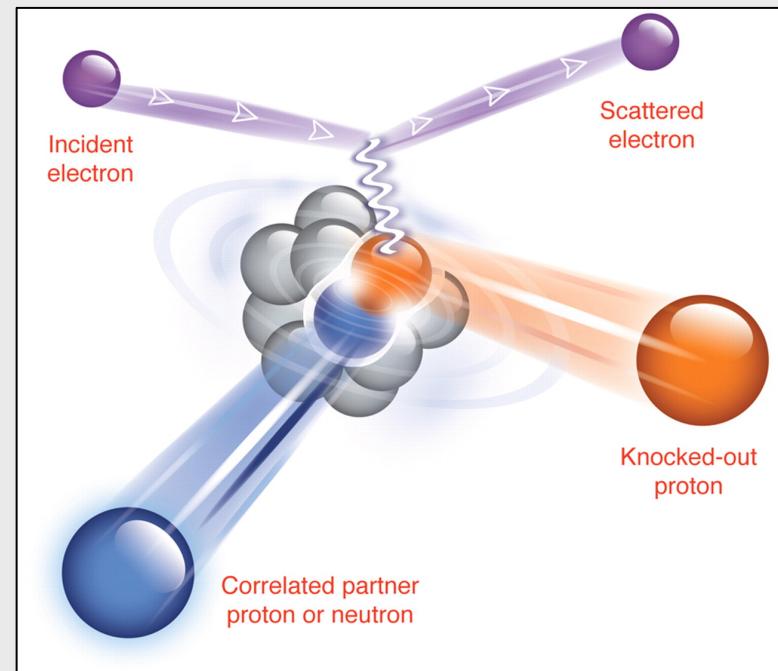
No such addition required  
for antineutrinos. Slight  
reduction if anything.

**(-10 ± 7)% of QE events**

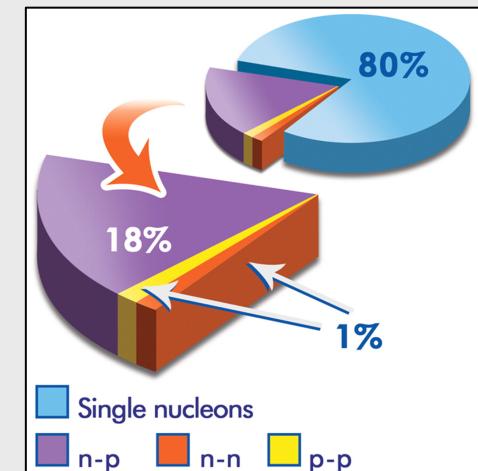


# Interpretation #2: Vertex Energy

- What do multi-nucleon models predict?
  - For short-range correlations, electron-scattering measurements on  $^{12}\text{C}$  indicate a predominance of **np** pairs in the initial state
  - Implies final states of **nn** in antineutrino and **pp** in neutrino CC scattering
  - For other forms of correlation, depends on model
- FSI a challenge in this analysis, but
  - All systematics considered as in  $d\sigma/dQ^2$  analysis
  - Neutrino / antineutrino correlation = +0.7
  - Hard to explain opposite trend with any of our systematics



R. Subedi et al.,  
Science 320, 1476  
(2008)



# Summary of Results

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- MINERvA has measured the differential cross-section  $d\sigma/dQ^2$  for neutrinos and antineutrinos on a hydrocarbon (CH) target
  - Integrated over the NuMI fluxes between 1.5 – 10 GeV
  - The shape of both of these cross-sections disfavor a simple RFG modeling of the carbon nucleus for scattering at these energies, strengthening the call for improved modeling in (anti)neutrino scattering
  - The data most prefer a model derived from an observed enhancement of the transverse part of the cross-section in electron scattering attributed to meson exchange currents, a form of long-range multi-nucleon correlation
- MINERvA has investigated the energy very near the vertex in CCQE rich samples for both neutrinos and antineutrinos
  - The GENIE Monte Carlo under-predicts the amount of low-energy hadronic particle content in the neutrino sample
  - A model-dependent fit (assume protons) indicates that an additional sub-200 MeV proton in  $(25 \pm 9)\%$  of QE events is consistent with the data

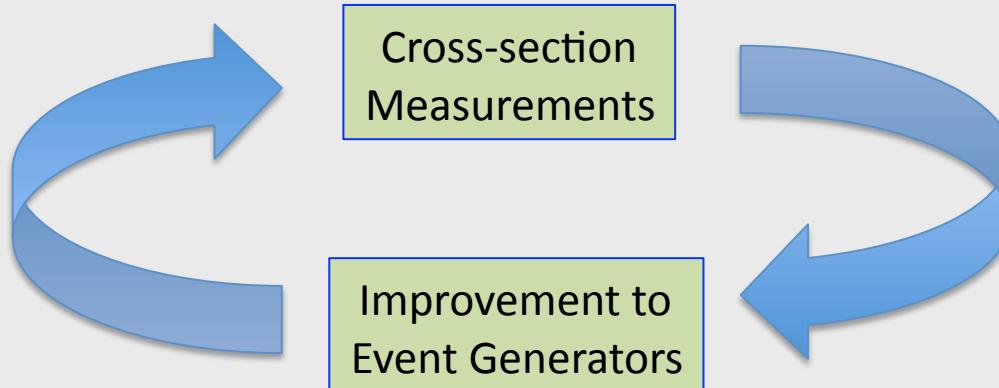
# Future Directions In CCQE @ MINERvA

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- Further quantify *correlations between neutrino and antineutrino* systematics
- *Michel electron tag* in neutrino sample  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- *Neutron tagging* in antineutrino sample
- $\mu + p$  reconstruction. Push on *low-energy tracking* threshold of protons to reconstruct final states like  $\mu + p + p$
- *Double-differential* cross sections in muon kinematics 
$$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$$
- QE cross section vs. energy,  $\sigma_{QE}(E)$
- Extend to *lower muon energies* by not requiring MINOS reconstruction
- QE scattering on other *nuclear targets* (Fe, Pb) in MINERvA
- *QE-like* final state cross sections

# Some Closing Remarks

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- These results are one example of new data in neutrino-nucleus scattering that can help us improve modeling of these processes
- A feedback loop is critical to get the most out of these data and to eventually come away with an improved generator for the future
- Many are aware; lots of buy-in from the community; upcoming workshops
  - [Neutrino-Nucleus Generators Workshop](#), University of Pittsburgh, June 9-11
  - [INT Workshop on Neutrino-Nucleus Scattering for Oscillation Exp](#), Dec 3-13

# Some Closing Remarks

- MINERvA looks forward to being an integral part of this effort to improve neutrino interaction modeling for future neutrino experiments and providing lots of input to the process
  - >20 students working on Ph.Ds – partial list of measurements

- 1) "Differential Cross Sections vs Q2 in Muon Anti-Neutrino Quasi-Elastic Interactions"
- 2) "Differential Cross Sections vs Q2 in Muon Neutrino Quasi-Elastic Interactions"
- 3) "Differential Cross Sections vs Q2 in Electron Neutrino Quasi-Elastic Interactions"
- 4) "Activity near the interaction vertex in Neutrino and Anti-neutrino Quasi-Elastic Interaction vertices"
- 5) "Comparisons of Neutrino Quasi-Elastic scattering on carbon, lead, iron and scintillator"
- 6) "Absolute Cross Sections vs neutrino Energy, muon momentum and angle in Muon Anti-Neutrino Quasi-Elastic Interactions"
- 7) "Absolute Cross Sections vs neutrino Energy, muon momentum and angle in Muon Neutrino Quasi-Elastic Interactions"
- 8) "Measurement of the Total Neutrino Charged Current Cross Section on Scintillator"
- 9) "Measurement of the Total Anti-Neutrino Charged Current Cross Section on Scintillator"
- 10) "Ratios of Neutrino and Anti-Neutrino Total Charged Current Cross-sections on carbon, lead, iron and scintillator"
- 11) "Kinematics of Inclusive Charged Current Scattering by neutrinos on Scintillator from 2-8GeV"
- 12) "Kinematics of Inclusive Charged Current Scattering by anti-neutrinos on Scintillator from 2-8GeV"
- 13) "Charged Pion production in Neutrino Charged Current scattering"
- 14) "Charged Pion production in Anti-Neutrino Charged Current scattering"
- 15) "Neutral Pion production in Neutrino Charged Current scattering"
- 16) "Neutral Pion production in Anti-Neutrino Charged Current scattering"
- 17) "Coherent Charged Pion production by Muon Neutrinos at 2-20GeV"
- 18) "Coherent Neutral Pion production by Muon Neutrinos at 2-20GeV"
- 19) "Coherent Charged Pion production by Muon Anti-Neutrinos at 2-20GeV"
- 20) "Strange Particle Production in 2-10GeV neutrinos and anti-neutrinos"
- 21) "Nuclear Dependence of Coherent Charged Pion production from 2-10GeV"
- 22) "Absolute Neutrino Cross Sections on Helium vs Neutrino Energy"
- 23) "Ratios of Inclusive Neutrino and Anti-Neutrino Charged Current Cross-sections on helium, carbon, iron, lead and scintillator"
- 24) "Structure Functions on Scintillator from 2-20GeV"

- Preparing now for continued data taking in the high-energy beam starting this summer
  - Increased statistics, but also expanded physics reach at higher energies

# The MINERvA Detector Calibration and Performance

L. Aliaga<sup>a</sup>, A. Bodek<sup>c</sup>, R. Bradford<sup>c</sup>, H. Budd<sup>c</sup>, A. Butkevich<sup>1</sup>, D.A.M. Caicedo<sup>e</sup>, C.M. Castromonte<sup>e</sup>, M.E. Christy<sup>f</sup>, J. Chvojka<sup>c</sup>, H. da Motta<sup>e</sup>, D.S. Damiani<sup>a</sup>, M. Datta<sup>f</sup>, R. DeMaat<sup>g</sup>, J. Devan<sup>a</sup>, S.A. Dytman<sup>h</sup>, G. A. Díaz<sup>b</sup>, B. Eberly<sup>h</sup>, D.A. Edmondson<sup>a</sup>, J. Felix<sup>i</sup>, L. Fields<sup>j</sup>, G. A. Fiorentini<sup>e</sup>, A. M. Gago<sup>n</sup>, H. Gallagher<sup>l</sup>, B. Gobbi<sup>j</sup>, R. Gran<sup>m</sup>.

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M.C.  
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## Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

A. M. M. L. Fields,<sup>1</sup> J. Chvojka,<sup>2</sup> L. Aliaga,<sup>3, 4</sup> O. Altinok,<sup>5</sup> A. Bodek,<sup>2</sup> D. Boehlein,<sup>6</sup> R. Bradford,<sup>2</sup> W.K. Brooks,<sup>7</sup> H. Budd,<sup>2</sup> A. Butkevich,<sup>8</sup> D.A.M. Caicedo,<sup>9</sup> C.M. Castromonte,<sup>9</sup> M.E. Christy,<sup>10</sup> H. da Motta,<sup>9</sup> D.S. Damiani,<sup>3</sup> I. Danko,<sup>11</sup> M. Datta,<sup>10</sup> M. Day,<sup>2</sup> R. DeMaat,<sup>6, \*</sup> J. Devan,<sup>3</sup> G.A. Díaz,<sup>4</sup> S.A. Dytman,<sup>11</sup> B. Eberly,<sup>11</sup> D.A. Edmondson,<sup>3</sup> J. Felix,<sup>12</sup> T. Fitzpatrick,<sup>6, \*</sup> G.A. Fiorentini,<sup>9</sup> A.M. Gago,<sup>4</sup> H. Gallagher,<sup>5</sup> B. Gobbi,<sup>1, \*</sup> R. Gran,<sup>13</sup> D.A. Harris,<sup>6</sup> A. Higuera,<sup>12</sup> I.J. Howley,<sup>3</sup> K. Hurtado,<sup>9, 14</sup> M. Jenkins,<sup>15</sup> T. Kafka,<sup>5</sup> M.O. Kanter,<sup>3</sup> C. Keppel,<sup>10</sup> M. Kordosky,<sup>5</sup> A.H. Krajeski,<sup>5</sup> S.A. Kulagin,<sup>9</sup> T. Le,<sup>17</sup> A.G. Leister,<sup>5</sup> S. Manly,<sup>2</sup> J.G. C.D. O'Connor,<sup>16</sup> L. Rakoto,<sup>1</sup> D.W. Schmitz,<sup>2, 3</sup> P.A. Rodrigues,<sup>4</sup> L. Aliaga,<sup>5, 6</sup> O. Altinok,<sup>7</sup> A. Bodek,<sup>4</sup> D. Boehlein,<sup>3</sup> R. Bradford,<sup>4</sup> W.K. Brooks,<sup>8</sup> H. Budd,<sup>4</sup> A. Butkevich,<sup>9</sup> D.A.M. Caicedo,<sup>1</sup> C.M. Castromonte,<sup>1</sup> M.E. Christy,<sup>10</sup> J. Chvojka,<sup>4</sup> H. da Motta,<sup>1</sup> D.S. Damiani,<sup>5</sup> I. Danko,<sup>11</sup> M. Datta,<sup>10</sup> M. Day,<sup>4</sup> R. DeMaat,<sup>3, \*</sup> J. Devan,<sup>5</sup> G.A. Díaz,<sup>6</sup> S.A. Dytman,<sup>11</sup> B. Eberly,<sup>11</sup> D.A. Edmondson,<sup>5</sup> J. Felix,<sup>12</sup> L. Fields,<sup>13</sup> T. Fitzpatrick,<sup>3, \*</sup> A.M. Gago,<sup>6</sup> H. Gallagher,<sup>7</sup> B. Gobbi,<sup>13, \*</sup> R. Gran,<sup>14</sup> D.A. Harris,<sup>3</sup> A. Higuera,<sup>12</sup> I.J. Howley,<sup>5</sup> K. Hurtado,<sup>1, 15</sup> M. Jenkins,<sup>16</sup> T. Kafka,<sup>7</sup> M.O. Kanter,<sup>5</sup> C. Keppel,<sup>10</sup> M. Kordosky,<sup>5</sup> A.H. Krajeski,<sup>5</sup> S.A. Kulagin,<sup>9</sup> T. Le,<sup>17</sup> A.G. Leister,<sup>5</sup> G. Maggi,<sup>8, †</sup> E. Maher,<sup>18</sup> S. Manly,<sup>4</sup> W.A. Mann,<sup>7</sup> C.M. Marshall,<sup>4</sup> K.S. McFarland,<sup>4, 3</sup> C.L. McGivern,<sup>11</sup> A.M. McGowan,<sup>4</sup> A. Mislicvec,<sup>4</sup> J.G. Morfin,<sup>3</sup> J. Mousseau,<sup>19</sup> D. Naples,<sup>11</sup> J.K. Nelson,<sup>5</sup> G. Niculescu,<sup>20</sup> I. Niculescu,<sup>20</sup> N. Ochoa,<sup>6</sup> C.D. O'Connor,<sup>5</sup> J. Osta,<sup>3</sup> J.L. Palomino,<sup>1</sup> V. Paolone,<sup>11</sup> J. Park,<sup>4</sup> C.E. Patrick,<sup>13</sup> G.N. Perdue,<sup>4</sup> C. Peña,<sup>8</sup> L. Rakotondravohitra,<sup>3</sup> R. D. Ransome,<sup>17</sup> H. Ray,<sup>19</sup> L. Ren,<sup>11</sup> K.E. Sassin,<sup>5</sup> H. Schellman,<sup>13</sup> R.M. Schneider,<sup>5</sup> E.C. Schulte,<sup>17, ‡</sup> P. Sedita,<sup>4</sup> C. Simon,<sup>21</sup> F.D. Snider,<sup>3</sup> M.C. Snyder,<sup>5</sup> J.T. Sobczyk,<sup>22, 3</sup> C.J. Solano Salinas,<sup>15</sup> N. Tagg,<sup>23</sup> W. Tan,<sup>10</sup> B.G. Tice,<sup>17</sup> G. Tzanakos,<sup>24, \*</sup> J.P. Velásquez,<sup>6</sup> J. Walding,<sup>5, §</sup> T. Walton,<sup>10</sup> J. Wolcott,<sup>4</sup> B.A. Wolthuis,<sup>5</sup> G. Zavala,<sup>12</sup> D. Zhang,<sup>5</sup> and B.P. Ziemer<sup>21</sup>

N. C.  
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D. W.  
N. Tagg

## Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

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(The MINERvA Collaboration)

# Thank you !

# Backups

# Systematics - Antineutrino

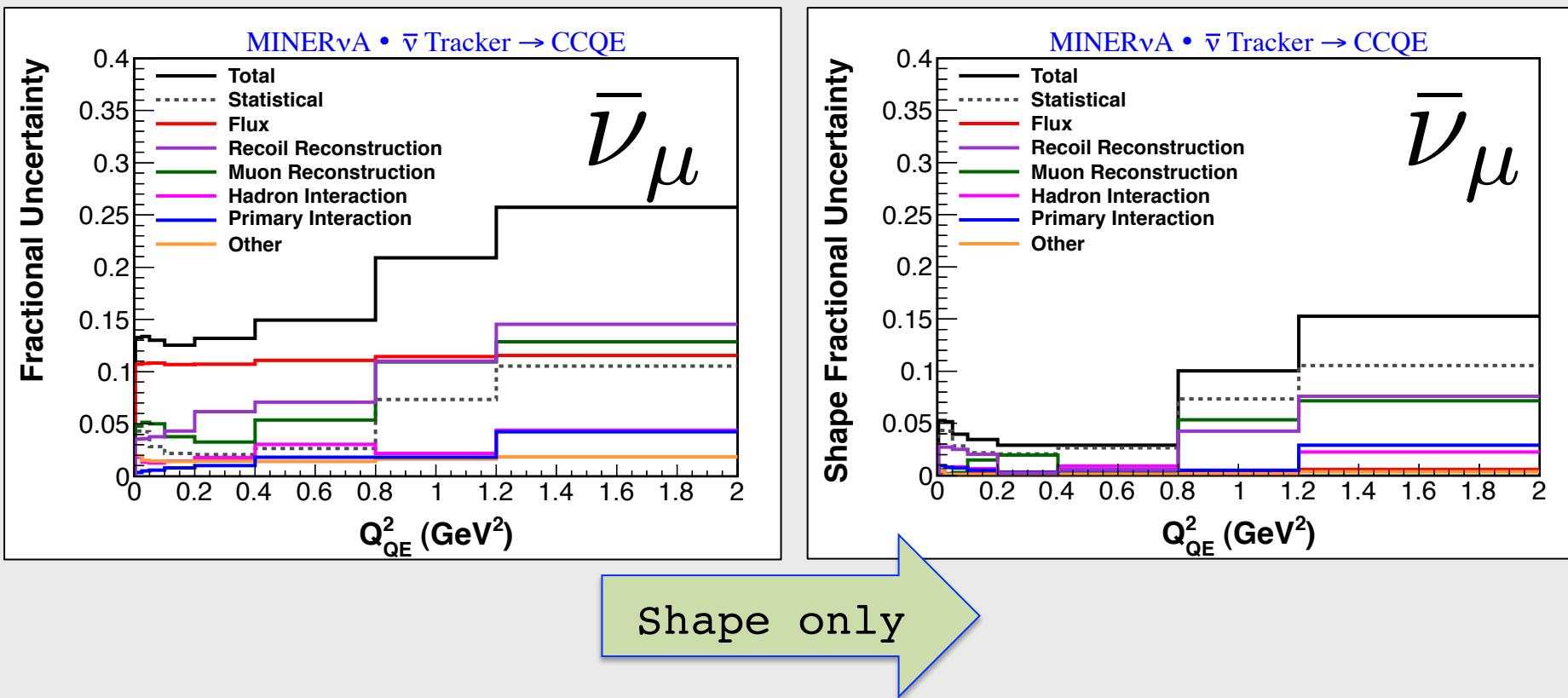
$\bar{\nu}_\mu$

$Q_{QE}^2$ (GeV $^2$ )	I	II	III	IV	V	VI	Total
0.0 – 0.025	0.05	0.04	0.00	0.02	0.11	0.02	0.13
0.025 – 0.05	0.05	0.04	0.01	0.01	0.11	0.02	0.13
0.05 – 0.1	0.05	0.04	0.01	0.01	0.11	0.01	0.13
0.1 – 0.2	0.04	0.04	0.01	0.01	0.11	0.01	0.12
0.2 – 0.4	0.03	0.06	0.01	0.02	0.11	0.01	0.13
0.4 – 0.8	0.05	0.07	0.02	0.03	0.11	0.01	0.15
0.8 – 1.2	0.11	0.11	0.02	0.02	0.11	0.02	0.20
1.2 – 2.0	0.13	0.15	0.04	0.04	0.12	0.02	0.23

TABLE I: Fractional systematic uncertainties on  $d\sigma/dQ_{QE}^2$  associated with muon reconstruction (I), recoil reconstruction (II), neutrino interaction models (III), final state interactions (IV), flux (V) and other sources (VI). The final column shows the total fractional systematic uncertainty due to all sources.

# Systematics - Antineutrino

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



# Systematics - Neutrino

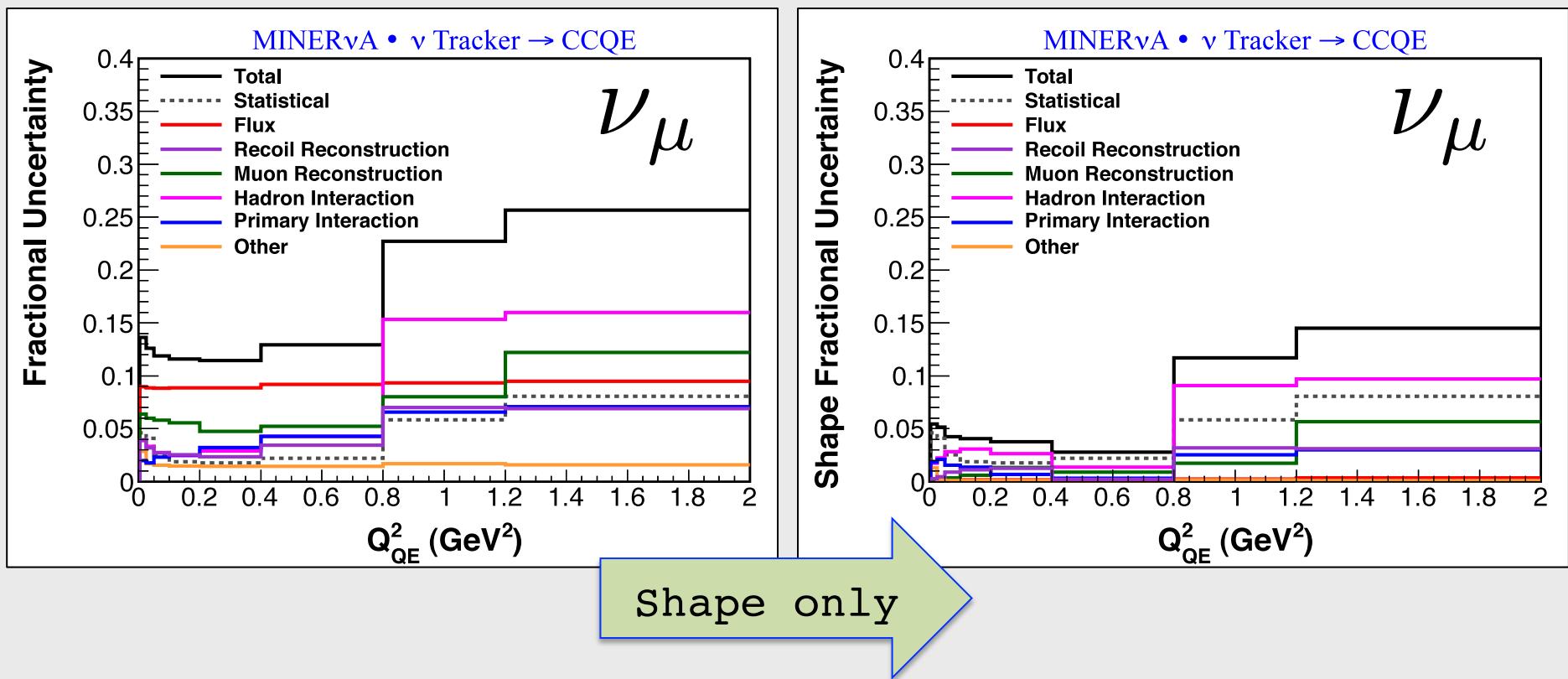
$\nu_\mu$

$Q_{QE}^2$ (GeV $^2$ )	I	II	III	IV	V	VI	Total
0.0 – 0.025	0.06	0.04	0.02	0.04	0.09	0.03	0.13
0.025 – 0.05	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.05 – 0.1	0.06	0.03	0.02	0.03	0.09	0.02	0.12
0.1 – 0.2	0.06	0.03	0.03	0.02	0.09	0.02	0.11
0.2 – 0.4	0.05	0.02	0.03	0.03	0.09	0.01	0.11
0.4 – 0.8	0.05	0.03	0.04	0.04	0.09	0.01	0.13
0.8 – 1.2	0.08	0.07	0.07	0.15	0.09	0.02	0.22
1.2 – 2.0	0.12	0.07	0.07	0.16	0.09	0.02	0.24

TABLE I: Fractional systematic uncertainties on  $d\sigma/dQ_{QE}^2$  associated with (I) muon reconstruction, (II) recoil reconstruction, (III) neutrino interaction models, (IV) final state interactions, (V) flux and (VI) other sources. The rightmost column shows the total fractional systematic uncertainty due to all sources.

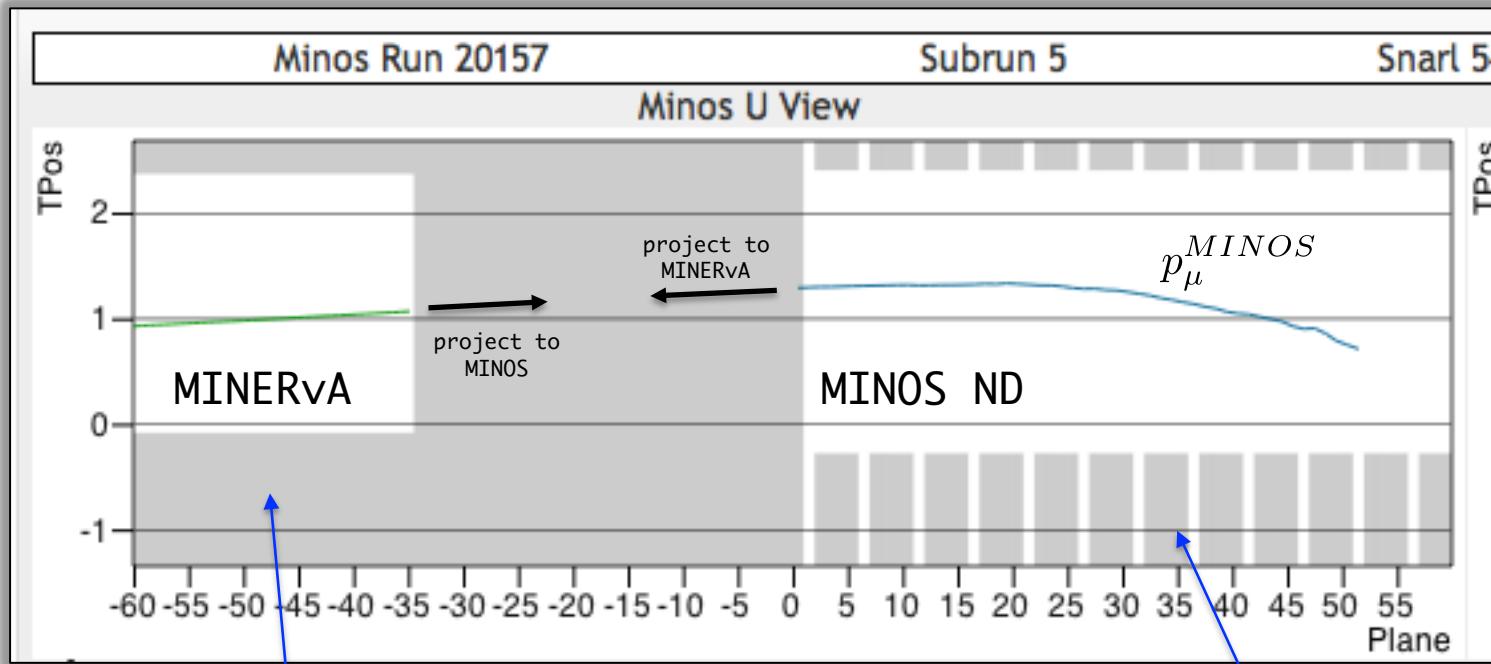
# Systematics - Neutrino

- Restricting to the *shape* of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



# Muon Tracking Efficiency

- Important to verify simulation of efficiencies against data wherever possible



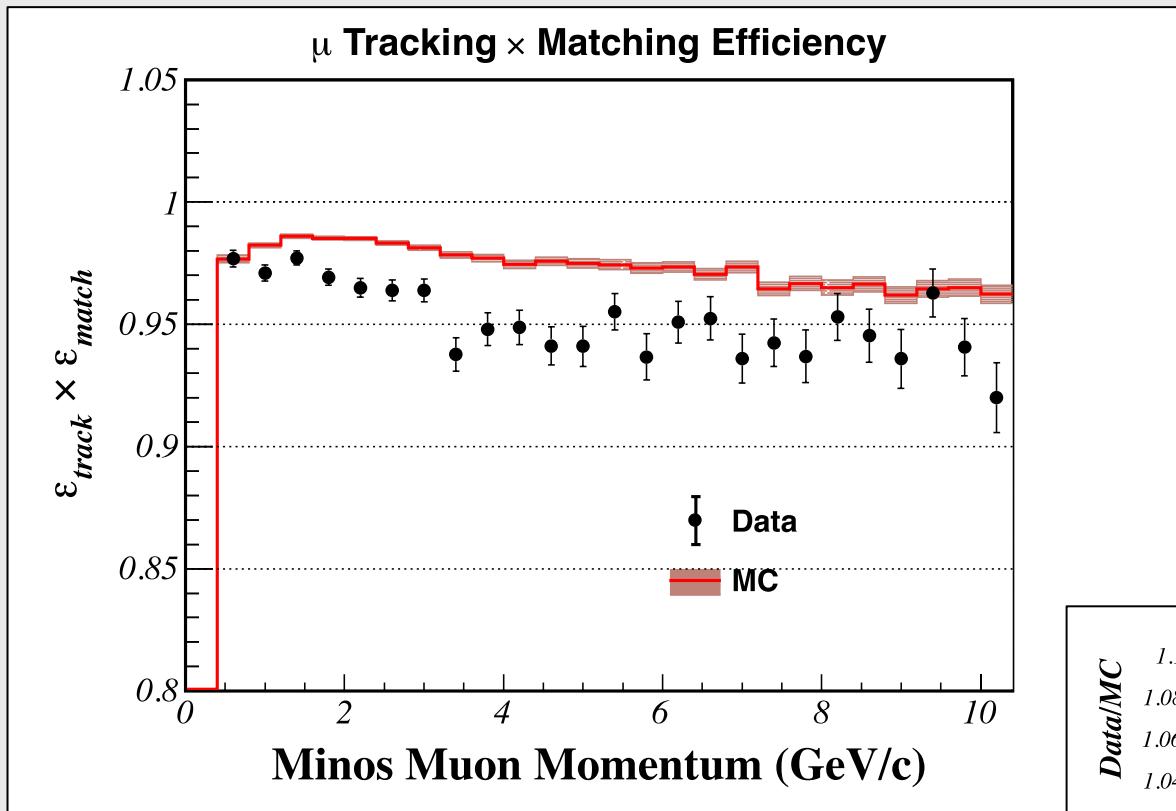
Affected by:

1. pile-up at high intensity
2. dead-time
3. large showers

Affected by:

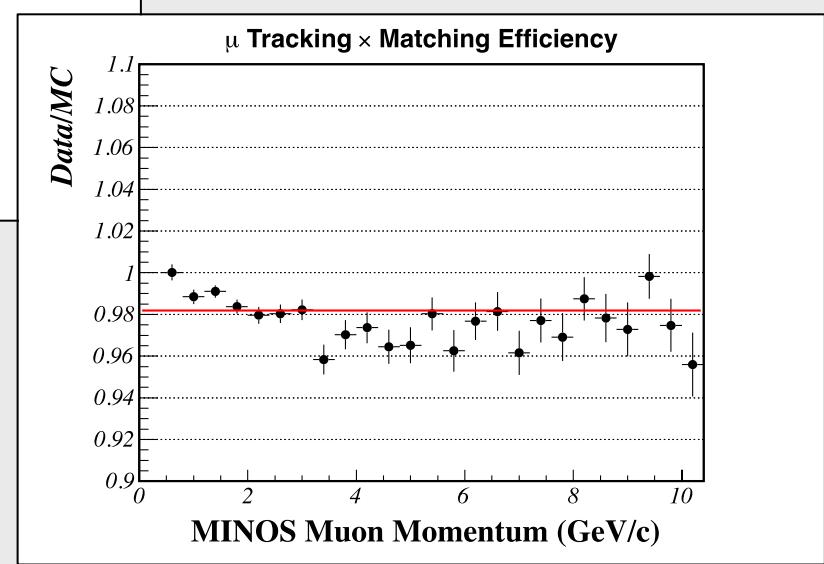
1. pile-up at high intensity, worse for shorter tracks (low energy)

# Muon Tracking Efficiency



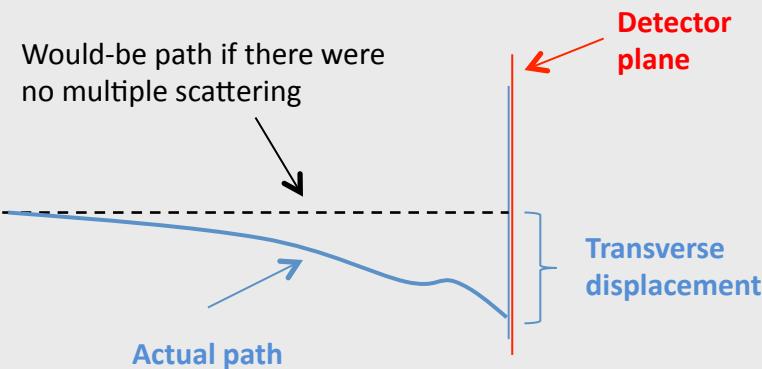
MINERVA muon  
tracking  
efficiency

Momentum provided  
by MINOS ND



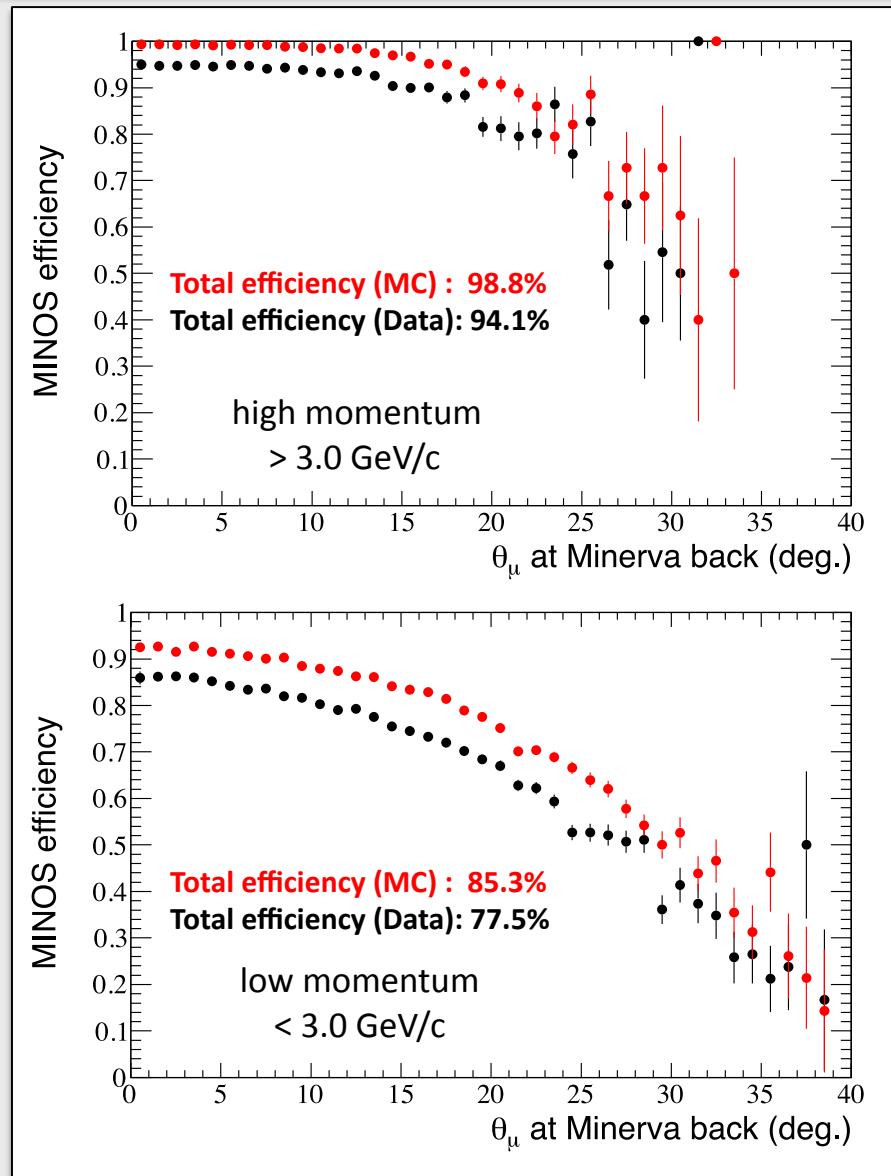
# Muon Tracking Efficiency

## MINOS muon tracking efficiency



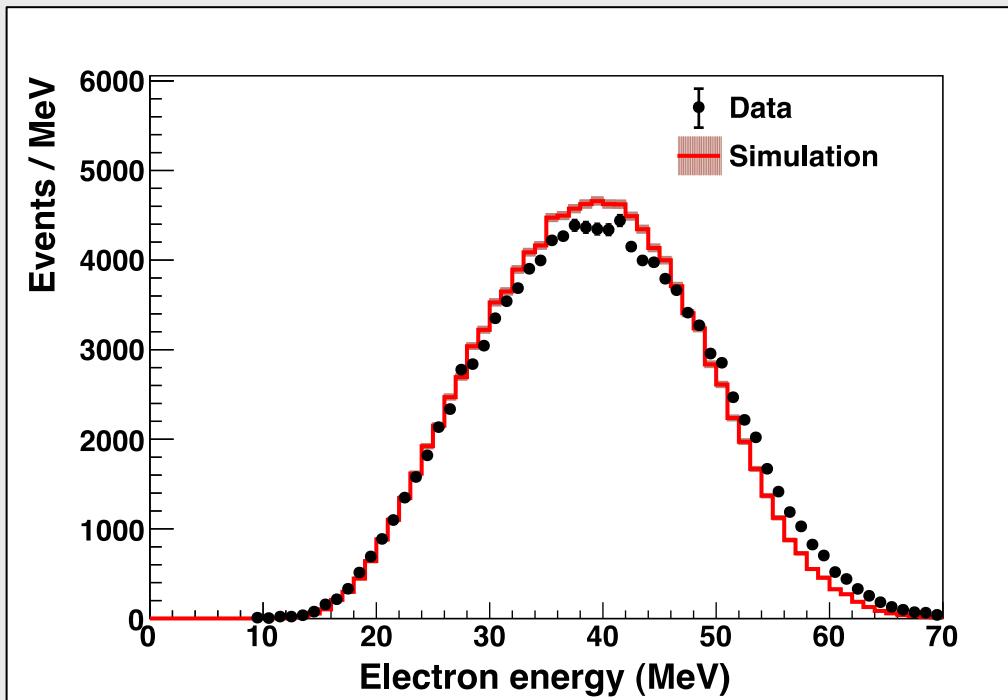
use scattering in MINERvA  
ECAL+HCAL to split into **high**  
and **low** momentum samples

Total Corrections	neutrinos	antineutrinos
$p_\mu < 3.0 \text{ GeV}/c$	$(-10.1 \pm 4.7) \%$	$(-7.8 \pm 3.4) \%$
$p_\mu > 3.0 \text{ GeV}/c$	$(-6.7 \pm 2.6) \%$	$(-4.5 \pm 1.9) \%$



# Electromagnetic Energy Scale

20 – 60 MeV electrons

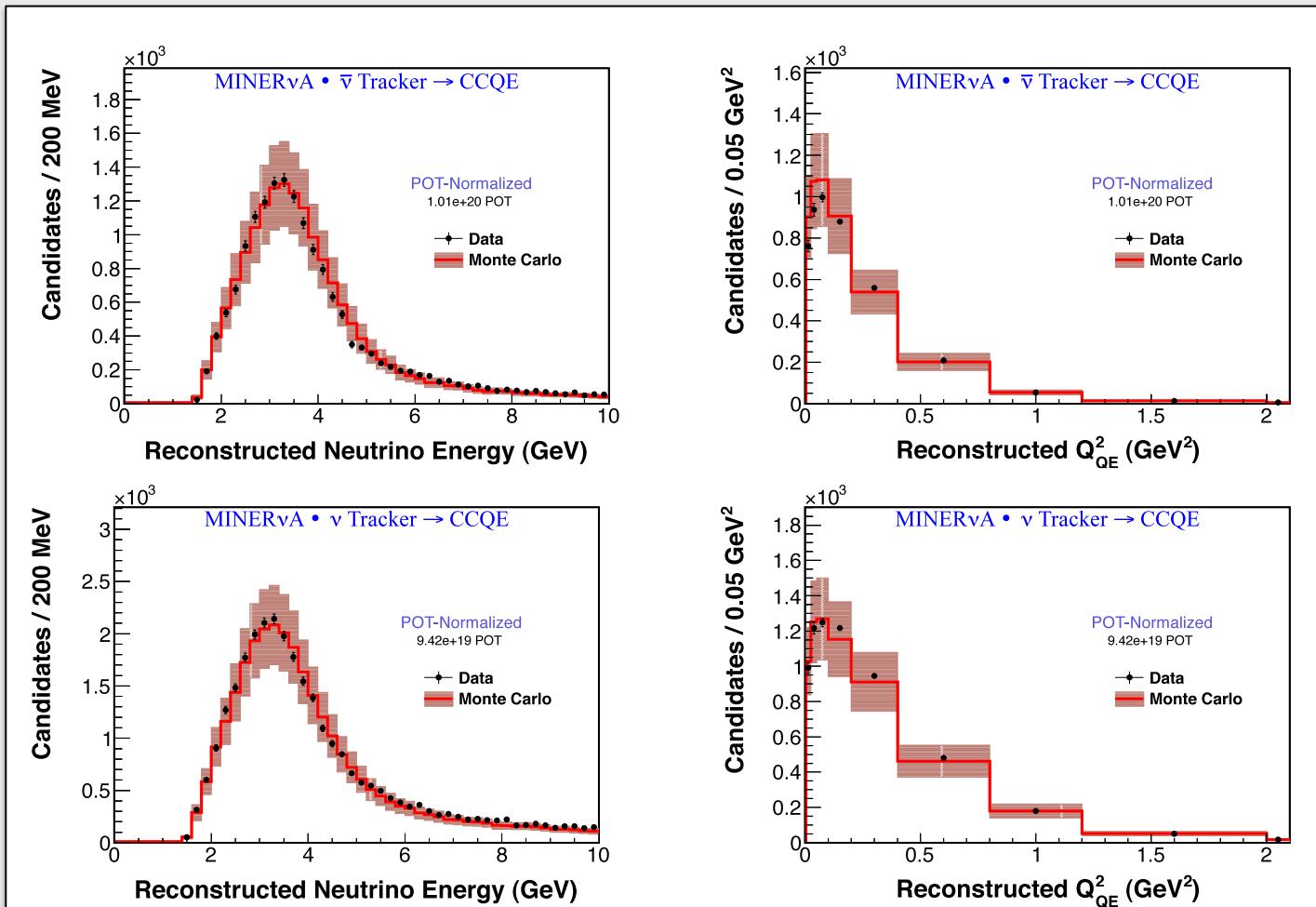


electromagnetic response  
uncertainty  $\approx 3\%$

# QE Event Candidates

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\mu - [(M_n - E_B)^2 + m_\mu^2 - M_p^2]}{2[(M_n - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} \left( E_\mu - \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu \right)$$



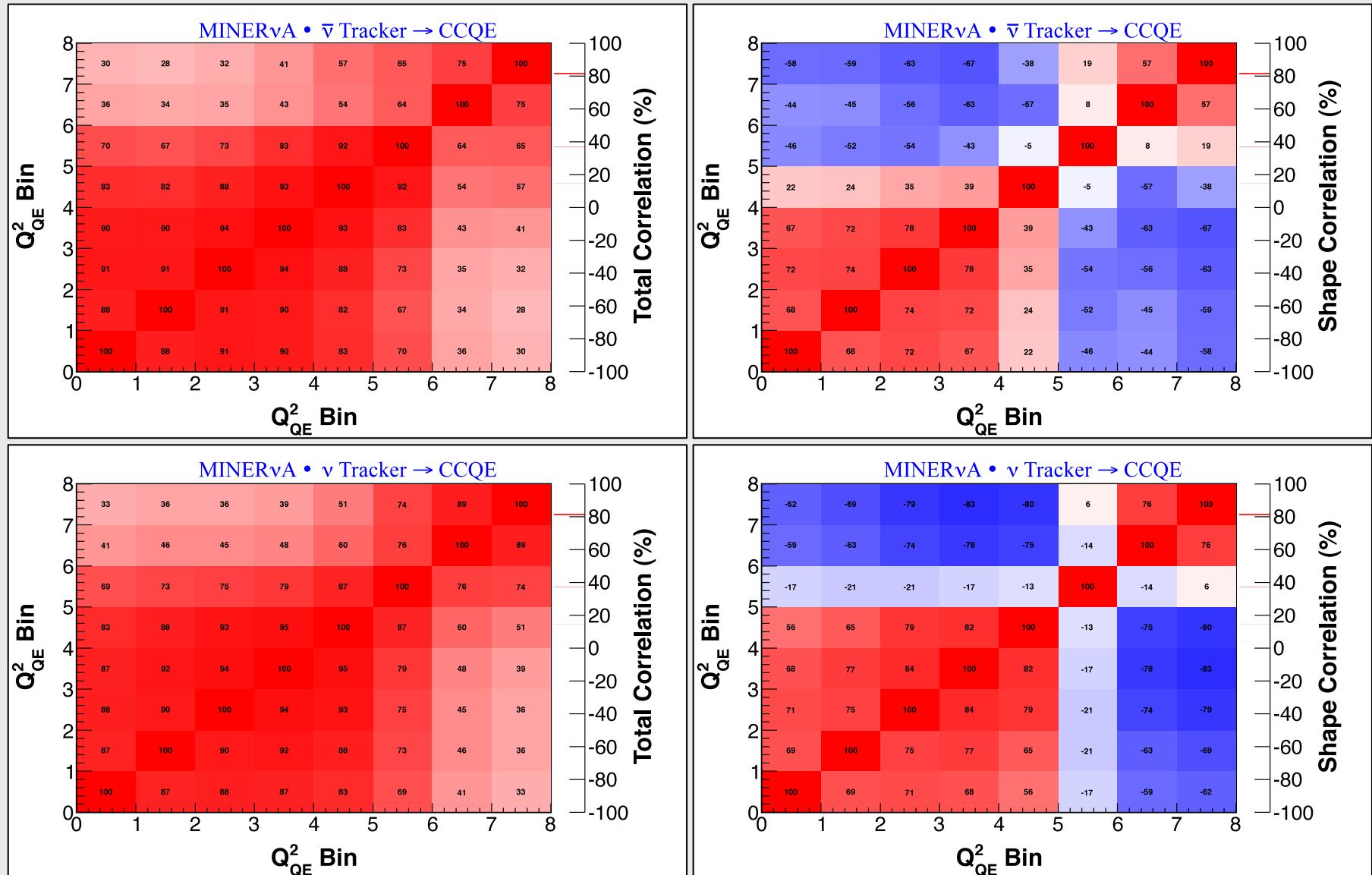
$\bar{\nu}_\mu$

16,467 events  
54% eff.  
77% purity

$\nu_\mu$

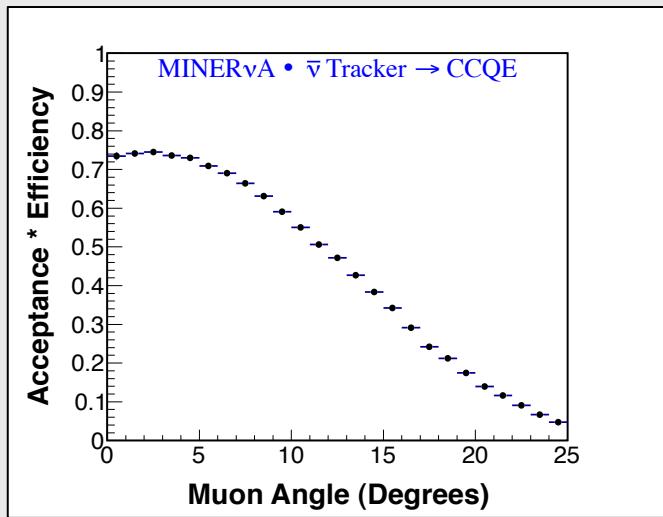
29,620 events  
47% eff.  
49% purity

# Correlation Matrices

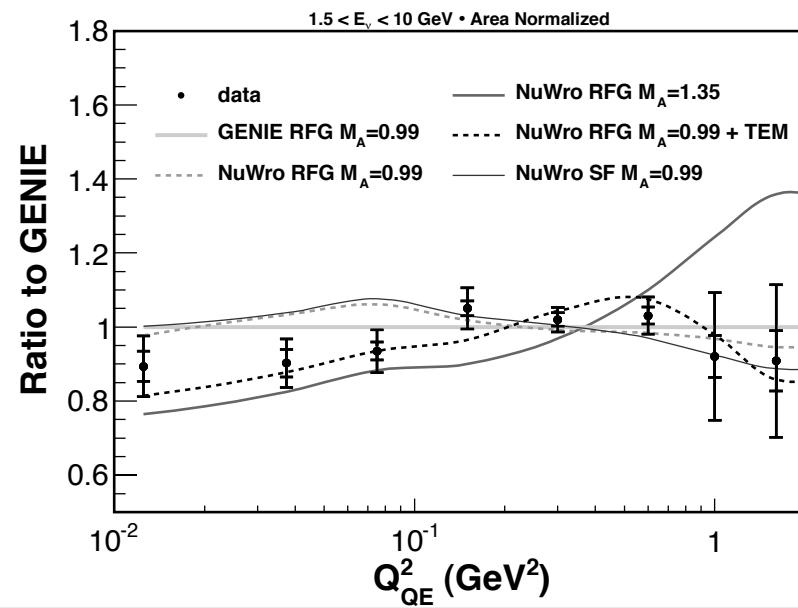
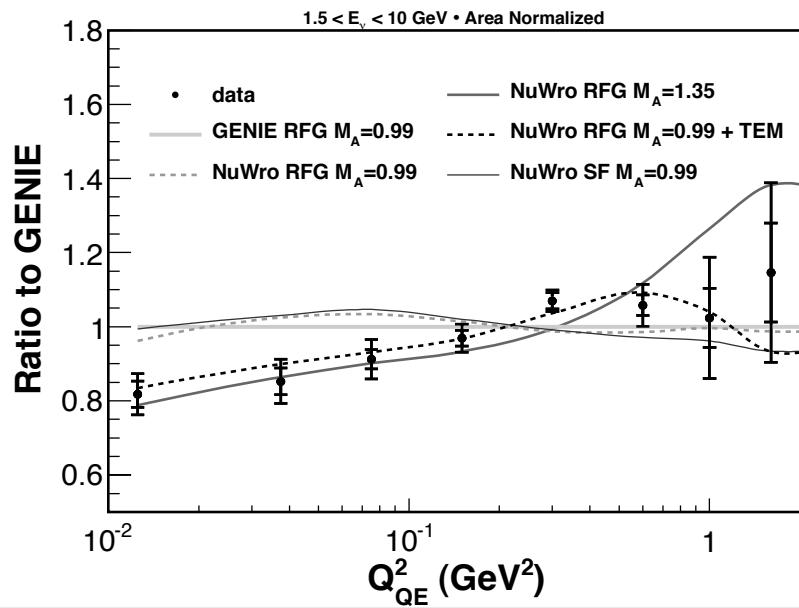
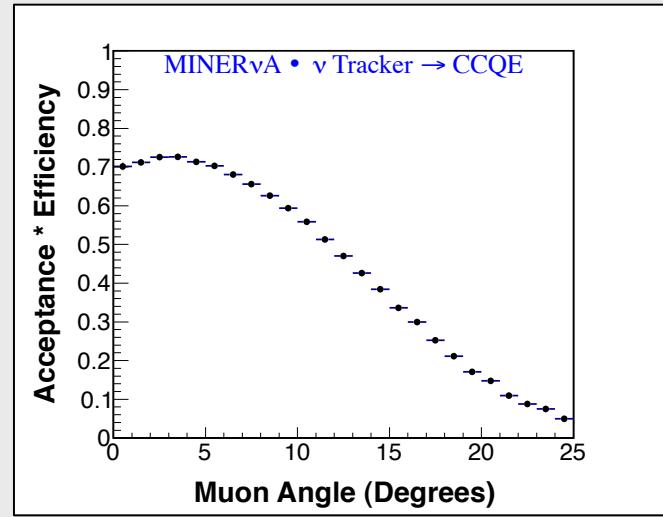


# 20 Degree Acceptance

$\bar{\nu}_\mu$

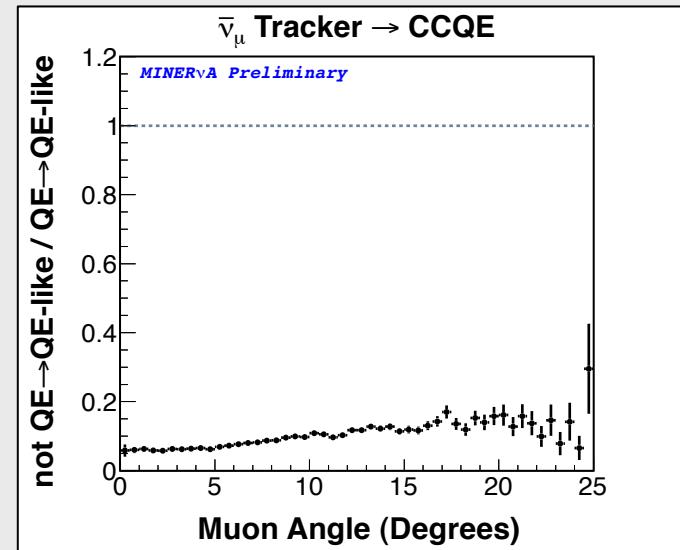
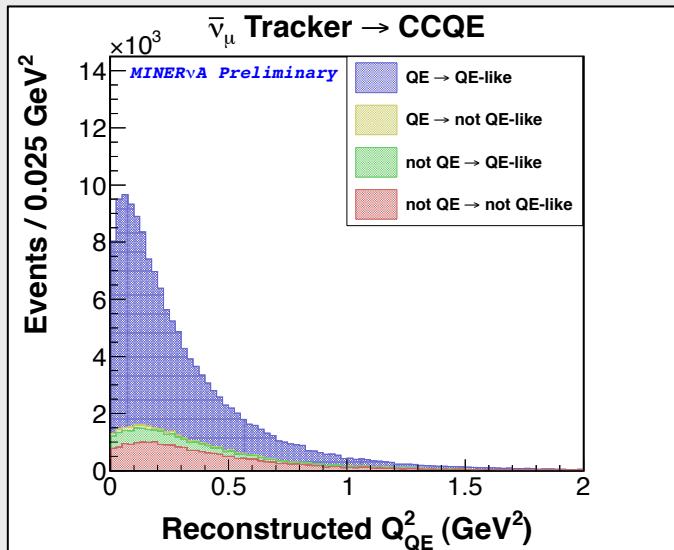


$\nu_\mu$

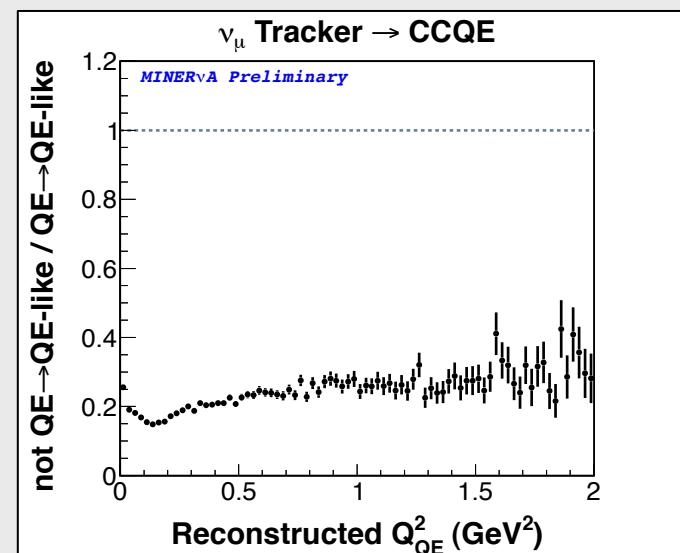
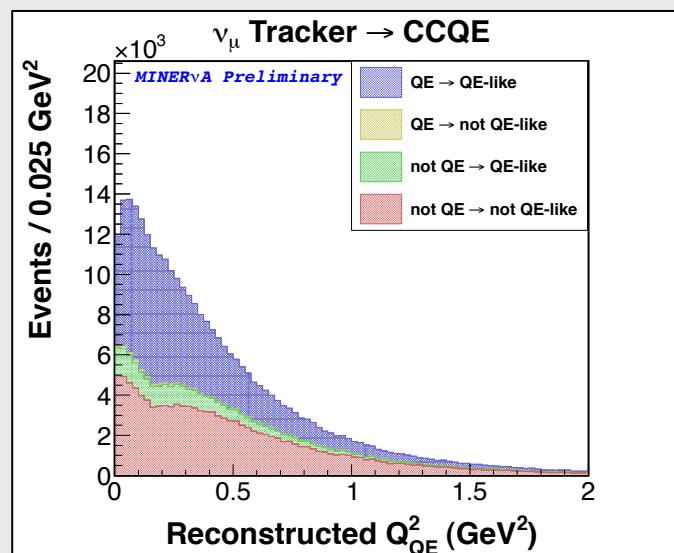


# QE vs. QE-like

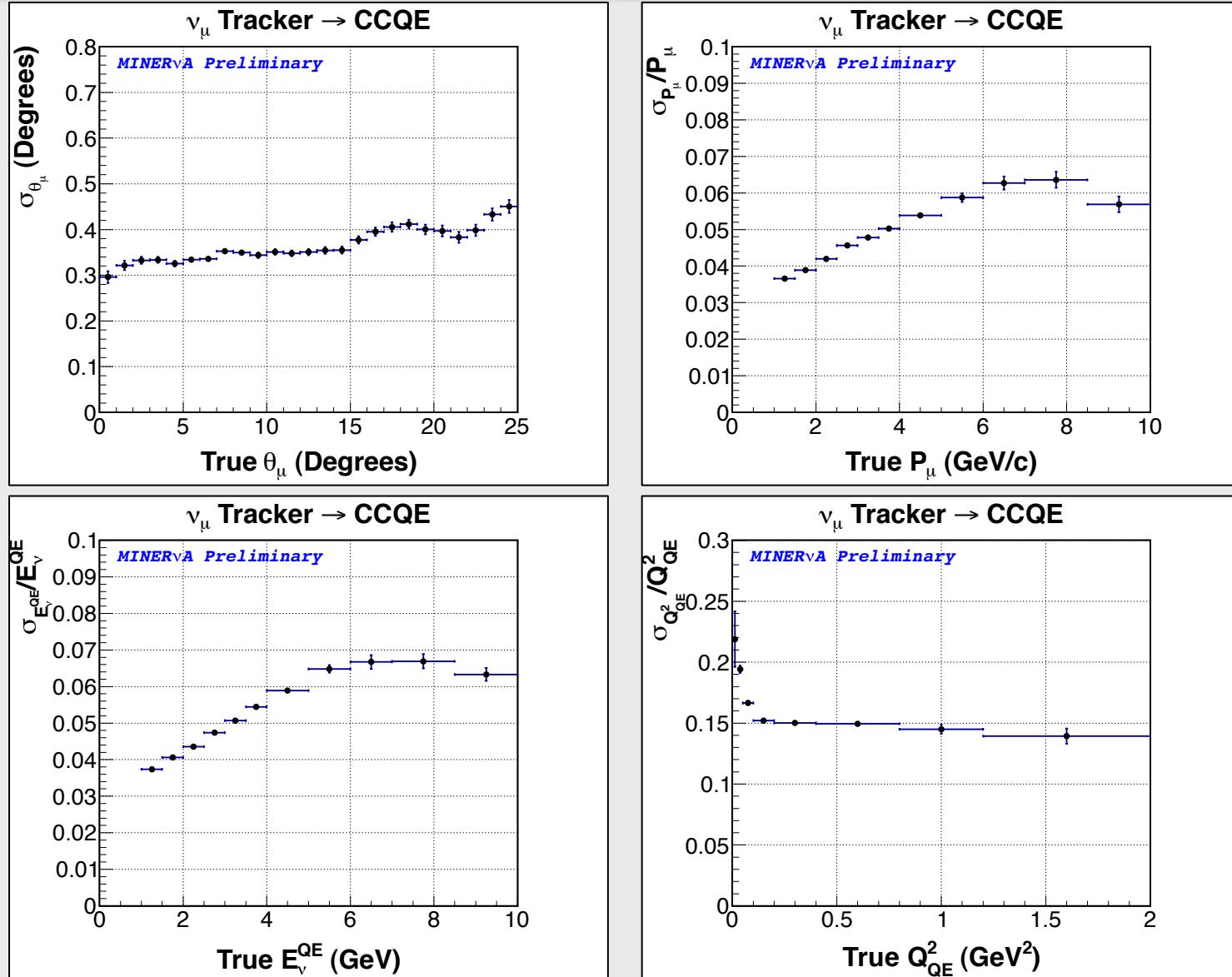
$\bar{\nu}_\mu$



$\nu_\mu$



# Resolutions



# GENIE Uncertainties

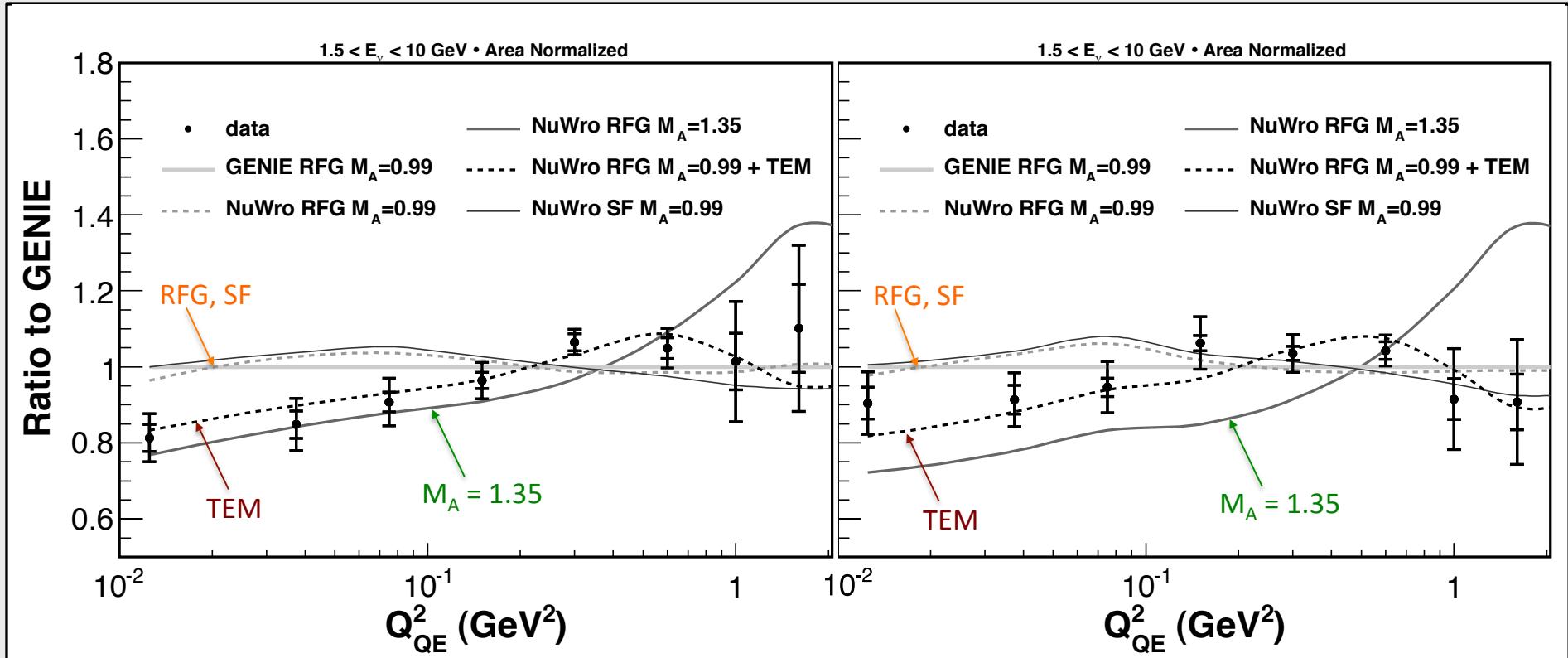
Uncertainty	GENIE Knob name	$1\sigma$
$M_A$ (Elastic Scattering)	MaNCEL	$\pm 25\%$
Eta (Elastic scattering)	EtaNCEL	$\pm 30\%$
$M_A$ (CCQE Scattering)	MaCCQE	+25% -15%
CCQE Normalization	NormCCQE	+20% -15%
$M_A$ (CCQE Scattering, shape only)	MaCCQEShape	$\pm 10\%$
CCQE Vector Form factor model	VecFFCCQEShape	
CC Resonance Normalization	NormCCRES	$\pm 20\%$
$M_V$ (Resonance Production)	MaRES	$\pm 20\%$
$M_V$ (Resonance Production)	MvRES	$\pm 10\%$
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp1pi	$\pm 50\%$
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn1pi	$\pm 50\%$
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	Rvp2pi	$\pm 50\%$
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	Rvn2pi	$\pm 50\%$
DIS CC Normalization	NormDISCC	??
Modfly Pauli blocking (CCQE) at low $Q^2$	CCQEPAULISUPVIAKF	$\pm 30\%$

Uncertainty	GENIE Knob name	$1\sigma$
Pion mean free path	MFP_pi	$\pm 20\%$
Nucleon mean free path	MFP_N	$\pm 20\%$
Pion fates – absorption	FrAbs_pi	$\pm 30\%$
Pion fates – charge exchange	FrCEEx_pi	$\pm 50\%$
Pion fates – Elastic	FrElas_pi	$\pm 10\%$
Pion fates – Inelastic	FrInel_pi	$\pm 40\%$
Pion fates – pion production	FrPiProd_pi	$\pm 20\%$
Nucleon fates – charge exchange	FrCEEx_N	$\pm 50\%$
Nucleon fates – Elastic	FrElas_N	$\pm 30\%$
Nucleon fates – Inelastic	FrInel_N	$\pm 40\%$
Nucleon fates – absorption	FrAbs_N	$\pm 20\%$
Nucleon fates – pion production	FrPiProd_N	$\pm 20\%$
AGKY hadronization model – $x_F$ distribution	AGKYxF1pi	$\pm 20\%$
Delta decay angular distribution	Theta_Delta2Npi	On/off
Resonance decay branching ratio to photon	RDecBR1gamma	$\pm 50\%$

# $d\sigma/dQ^2$ Shape

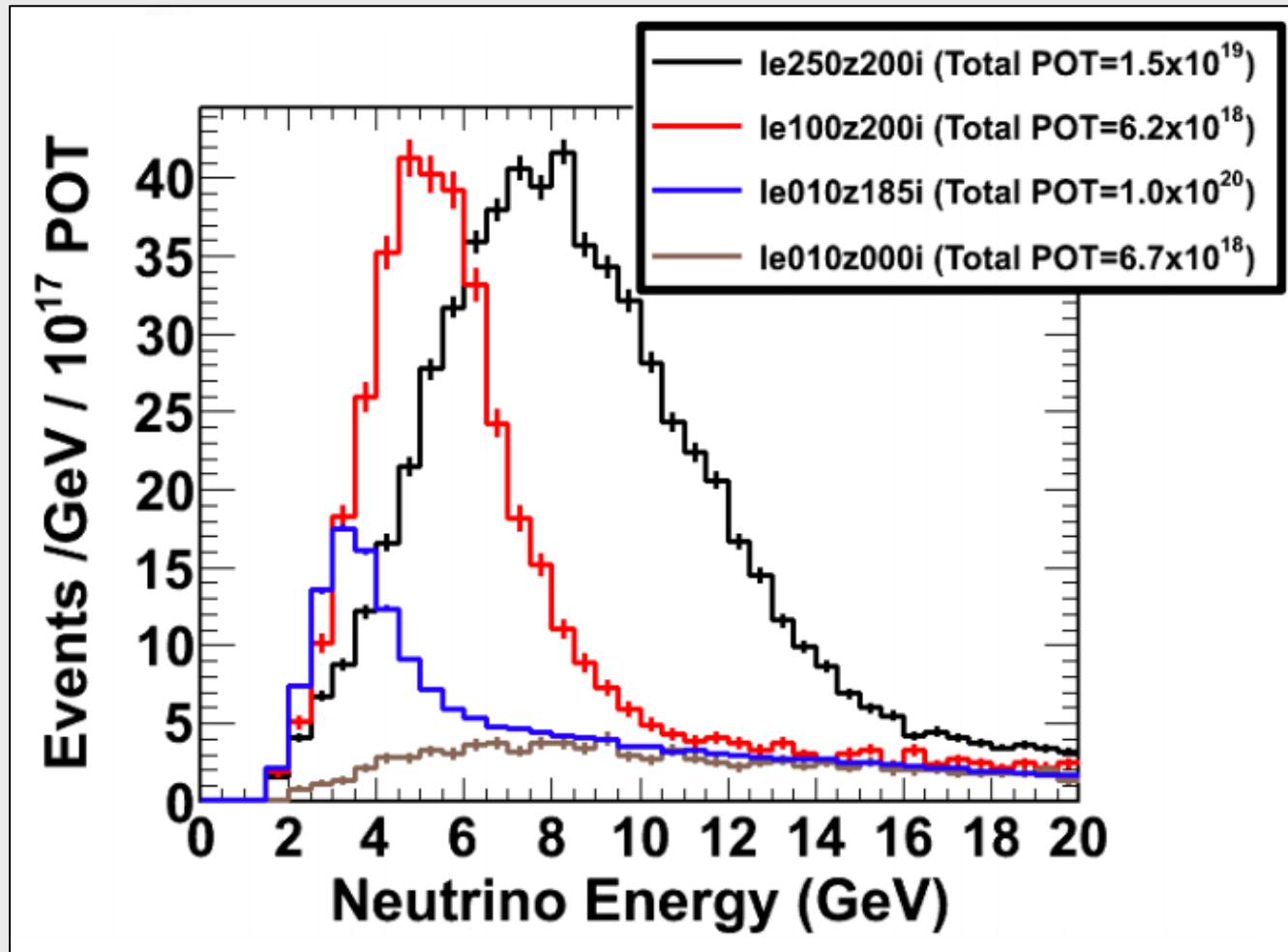
$\bar{\nu}_\mu$  CCQE

$\nu_\mu$  CCQE

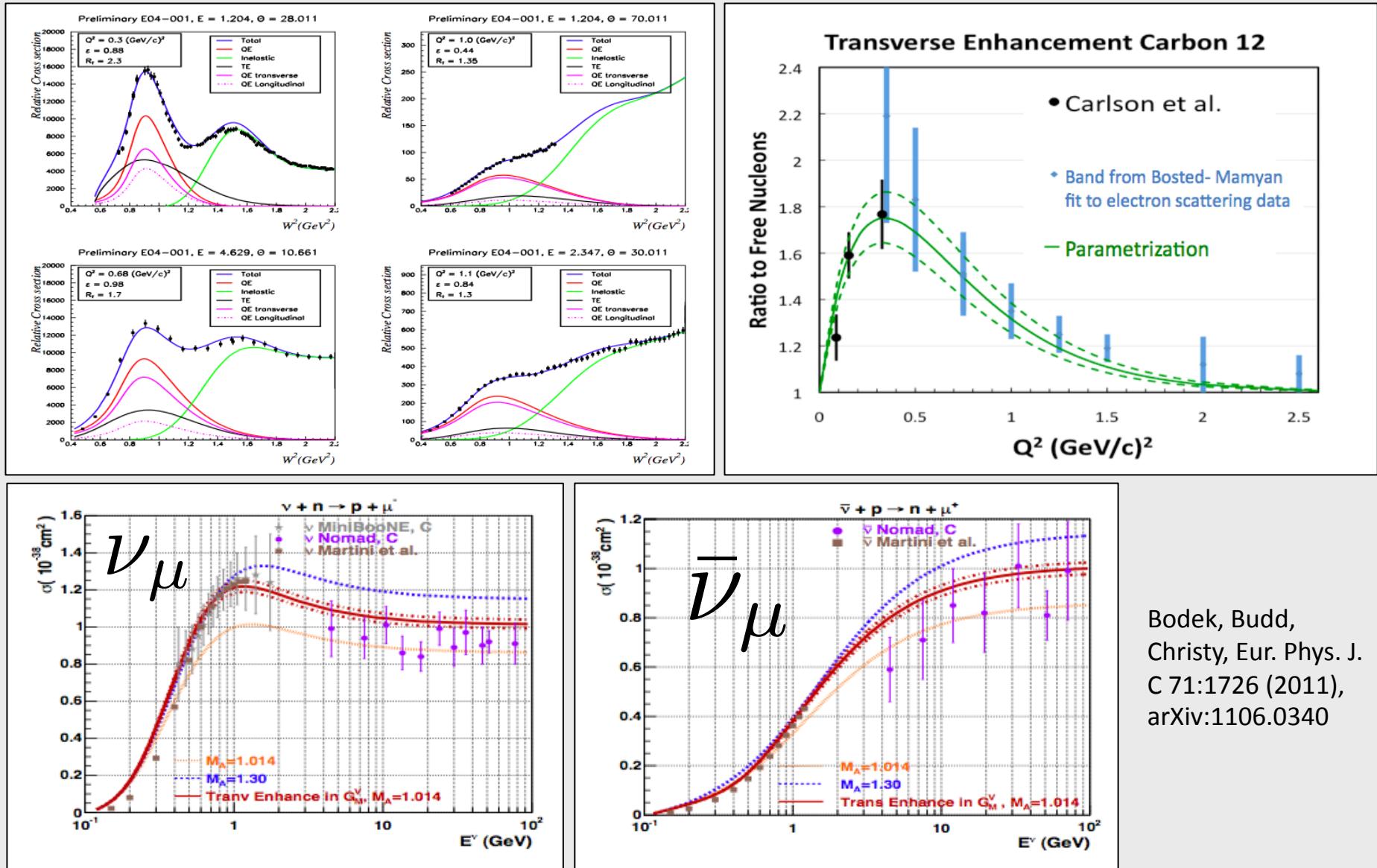


same plots with log x-axis to see low  $Q^2$  region

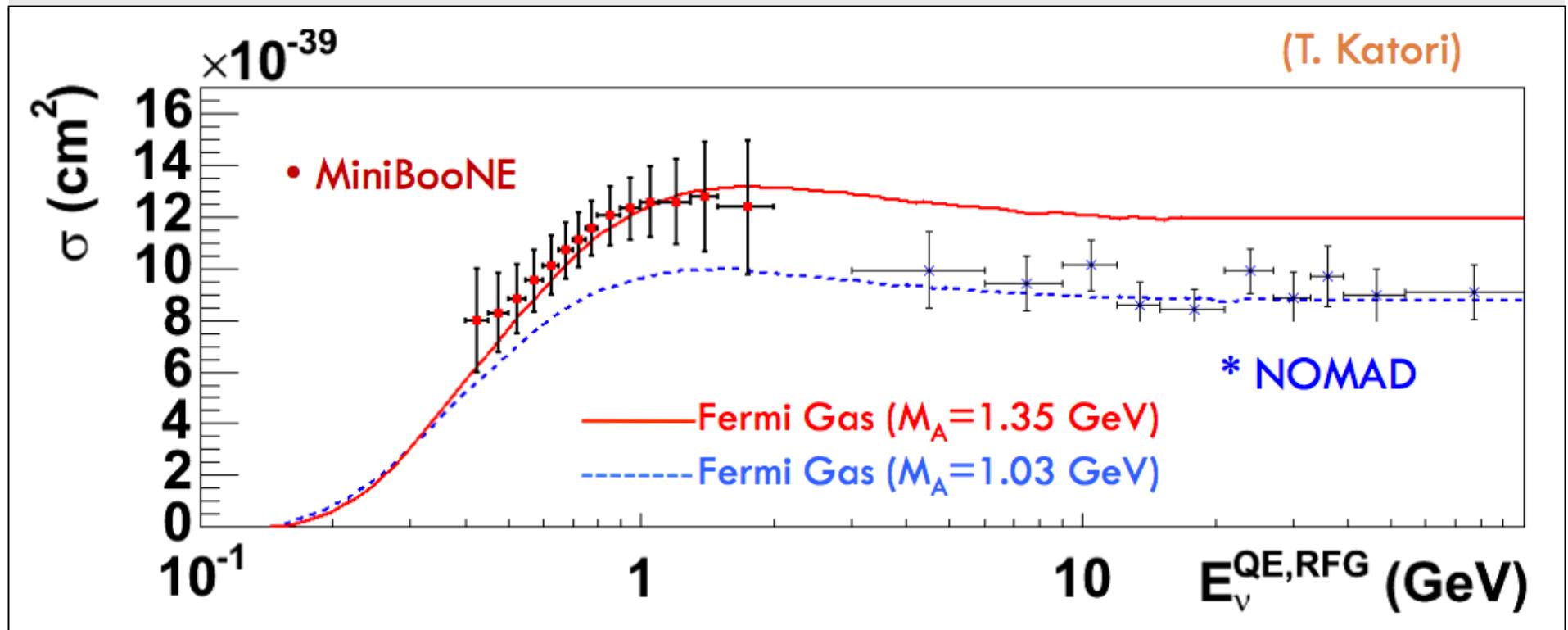
# Special Run Data



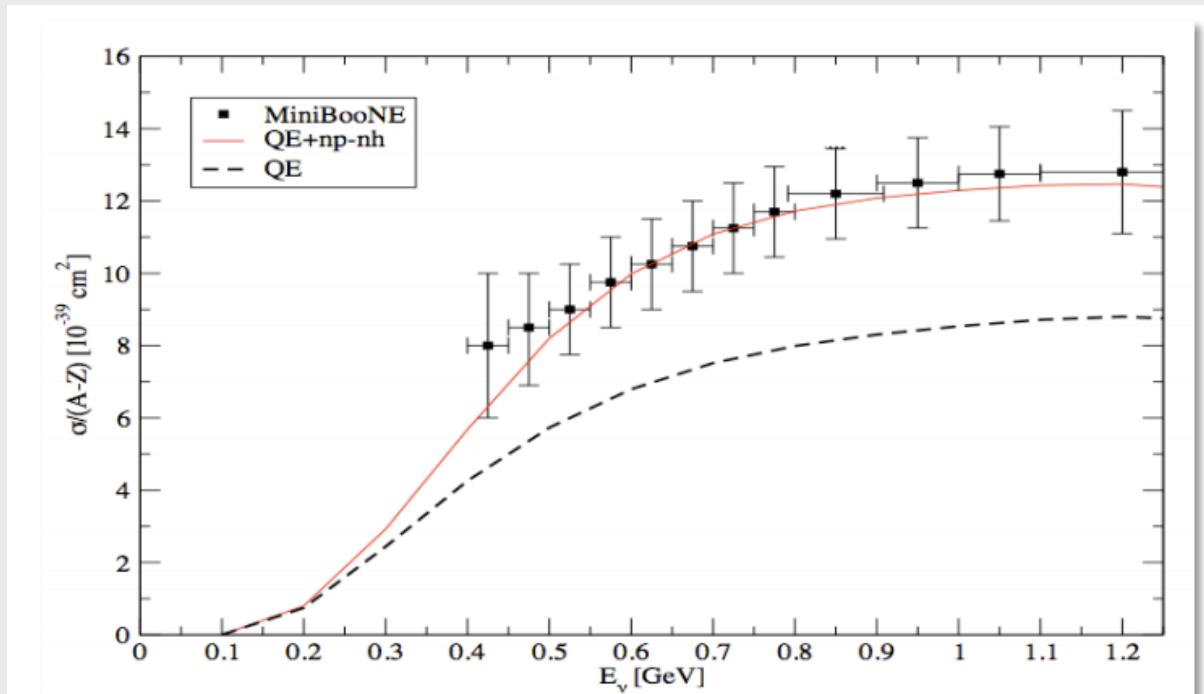
# Transverse Enhancement Model



# MiniBooNE vs. NOMAD



# 2p2h in MiniBooNE

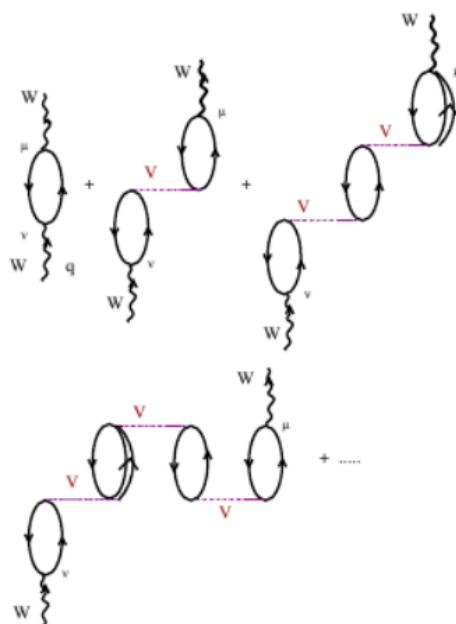


Martini et al., PRC 80, 065001 (2009)

## Why RPA (1)

RPA (random phase approximation) are nuclear collective effects which according to Martini and Nieves are necessary to reproduce MiniBooNE CCQE data.

- **Polarization (RPA) effects.** Substitute the  $ph$  excitation by an RPA response: series of  $ph$  and  $\Delta h$  excitations.



### 1. Effective Landau-Migdal interaction

$$V(\vec{r}_1, \vec{r}_2) = c_0 \delta(\vec{r}_1 - \vec{r}_2) \left\{ f_0(\rho) + f'_0(\rho) \vec{r}_1 \vec{r}_2 \right. \\ \left. + g_0(\rho) \vec{\sigma}_1 \vec{\sigma}_2 + g'_0(\rho) \vec{\sigma}_1 \vec{\sigma}_2 \vec{r}_1 \vec{r}_2 \right\}$$

Isoscalar terms  do not contribute to CC

2.  $S = T = 1$  channel of the *ph-ph* interaction  $\rightarrow$  s longitudinal ( $\pi$ ) and transverse ( $\rho$ ) + SRC

$$g'_0 \vec{\sigma}_1 \vec{\sigma}_2 \vec{\tau}_1 \vec{\tau}_2 \rightarrow [V_l(q) \hat{q}_i \hat{q}_j + V_t(q) (\delta_{ij} - \hat{q}_i \hat{q}_j)] \sigma_1^i \sigma_2^j \vec{\tau}_1 \vec{\tau}_2$$

$$V_{l,t}(q) = \frac{f_{\pi NN, \rho NN}}{m_{\pi, \rho}^2} \left( F_{\pi, \rho}(q^2) \frac{\vec{q}^2}{q^2 - m_{\pi, \rho}^2} + g'_{l,t}(q) \right)$$

### 3. Contribution of $\Delta h$ excitations important

- analogy:  
polarization effects,  
screening electric  
charge
  - form factors  
become  
renormalized.

# RPA Comparisons

